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Solar powered water purification system

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ENTITLED

Solar Powered Water Purification System

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Drazen Fabris
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Thesis Advisor

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Solar-Powered Water Purification System

By

Alina Carlson, Reece Kiriu, Andrew Nosé, Christopher Sugii, Erin Taketa, and Alex Tamai

THESIS

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Solar Powered Water Purification System

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Abstract

Santa Clara University's 2011-2012 Solar-Powered Water Purification System team is developing a solution to create a water distillation system, heated by solar troughs and solely powered by photovoltaic (PV) panels that can produce clean, drinkable water. This device would balance cost and efficiency to be marketable to lower-income locations, such as developing countries that suffer from shortages of clean water. In accomplishing this, the team will ensure that the system is sustainable and requires minimal maintenance.

Acknowledgments

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Section 1: Introduction

1.1 Project Background

The Institute of Medicine panel (part of the National Academy of Sciences) suggests that the average human consumes roughly eight cups of water per day to maintain a healthy lifestyle [1]. To citizens of the United States, this doesn't seem difficult to accomplish because running water is widely available. The abundance of fresh flowing water is common in developed nations, but is a privilege rarely experienced by those in the developing world. In fact, the shortage of water is a growing concern in many parts of the world, especially in developing or impoverished countries. It is ironic that such an issue could exist when over 75% of the Earth's surface is covered by water. However, a vast majority of that water is ocean water, which has a salinity level that is too high for human consumption. Through proper water desalination, the ocean can be a promising source of water, which could adequately provide for this growing need.

Currently, large investments are necessary for efficient, large-scale desalination systems which developing countries do not have. Unfortunately, these are the countries with the greatest need for fresh drinking water, as many of their current water sources are contaminated or insufficient in supply. As a result, 1.8 million people die from waterborne diseases every year [2]. Purifying water is a crucial process for drinking safety and requires not only removal of inorganic material but also bacterial treatment. To address this problem, there are numerous ongoing efforts to provide fresh water for impoverished communities. In Africa, many of these projects involve drilling wells to tap into the groundwater [4]. However, groundwater in Africa is limited and these wells must be dug deeper as the resource becomes depleted over time [5]. Therefore, alternative sources such as ocean water can supplement the substantial clean water demand and alleviate the reliance on groundwater.

A desalination system removes the salt from ocean water, transforming it into potable water through one of many purification processes. Distilling, or boiling the dirty or salty water to produce clean vapor that is then condensed back to water, is perhaps the simplest technique. The process requires boiling salt water at temperatures over 100 °C, a temperature at which bacteria is killed. Therefore, it is worthwhile to pursue an efficient yet low-cost desalination system that will increase the potential for widespread application for water purification. A desalination system can work in conjunction with the tapped wells to help alleviate hardships felt by the lack of clean water, not only in developing nations, but also in countries around the world.

1.2 Design Lineage

The Solar-Powered Water Purification System has been a part of the Santa Clara University Senior Design Conference series since 2006. Each consecutive team has built upon the successes of the previous team, utilizing the idea of solar thermal collection to provide the energy necessary for the water purification process. Due to the overly complex, expensive, and inefficient qualities of the past systems, the process has yet to be fully enhanced and achieve its maximum potential for clean water production. A major aspect of previous teams' designs was incorporating a vacuum pump to the system to effectively lower the pressure of the salt water in the boiler, thereby lowering the boiling temperature. In doing so, less energy would be needed to heat the water to the desired lower boiling point. Team Clean Water of 2011 pushed this concept, and was able to produce 11 liters of water per day. However, the system was never truly capable of maintaining the low-pressure requirement because leaks plagued the piping throughout the boiler and condenser; therefore, new ideas to reach the boiling point were considered. Professor Drazen Fabris, who advised the 2010-2011 Team Clean Water, along with Professor Abdlmonem Beitelmal, presented this project to the class during the 2011 Junior Convocation. Six members signed up to work on the project: Alina Carlson, Reece Kiriu, Andrew Nosé, Christopher Sugii, Erin Taketa, and Alex Tamai.

1.3 Statement of Project Goals

The major objective of the team's Solar-Powered Water Purification System is to produce clean, drinkable water using a simplified system that powered solely by the sun. To become a marketable, worldwide product, the system must be portable and durable enough to transport through all terrains and conditions over long periods of time. In addition, it should be inexpensive and user-friendly. Finally, for ease of shipping and transportation, the system should be able to fit in a standard shipping container. The combination of the system design constraints and objectives provide a strong base for the system to build upon in order to provide developing communities with clean drinking water. This system will contribute to the overall health and quality of life of those who lack clean drinking water resources. Utilizing solar parabolic trough designs, concentrated solar power is used to fuel active distillation of salt water by means of evaporation. The water vapor is condensed back into liquid form, thereby creating purified, clean water.

Section 2: System Level Analysis

2.1 Customer Needs

The team sought to design a solar-powered water purification system that not only maximized water production, but would also meet the needs of the potential consumers of the product. The potential consumer market includes developing countries near coastal regions, and disaster relief agencies. In order to more adequately design the system, the team interviewed Professor Steven Chiesa of Santa Clara University, Peace Corps volunteers, and the Santa Clara University President of Engineers Without Borders, Ashley Ciglar. Through the interviews, the team discovered important issues with regards to water purification and the targeted market.

Professor Steven Chiesa, a Civil Engineering professor at Santa Clara University, provided valuable insight regarding water purification in general. Since the team's targeted market includes coastal communities, it is important to be aware that ocean water could contain algae and microorganisms even after the distillation process. This could be remedied by introducing a pre-filtration process, via ultraviolet lights, or by heating the water to temperatures much higher than the boiling point. In addition, the ocean water could also contain volatile chemicals, such as solvents and industrial chemicals. These chemicals could be very detrimental to the system, as it could cause the boiler to explode. Therefore, pre-filtration is needed prior to the purification process if the ocean water is contaminated with chemicals.

The remaining interviews, conducted with the Peace Corps volunteers and Ashley Ciglar, provided insight for the lifestyle of Hondurans and Guatemalans. The interviews were particularly useful for gaining information on the targeted consumer groups. A major problem brought to the team's attention is that, although developing countries already possess filtration systems, they do not always know how to operate these systems. In addition, many local residents do not maintain or even use the foreign systems after the provider leaves. It is, therefore, very important for the team's system to be simple, easy to operate, and require little to no maintenance.

The interviews yielded important aspects that needed to be considered and incorporated into the new system. Table 1 summarizes the most important information obtained from the interviews. A Project Design Specification (PDS) report (Appendix L) was generated to identify goals for various elements of the system. In addition, a Quality Function Deployment (QFD) report (Appendix J) was created to match the customer needs with the engineering targets. Based on this report, the needs of the customer have been addressed, while also creating a system that is thoughtfully engineered.

Table 1: Summary of customer needs and market research from conducted interviews

Considerations
- Average rate of water consumption per person
- What is the water used for?
- Energy resources (oil, solar thermal)
- Types of water sources found in the area
- Amount of people system needs to provide for

Characteristics of Developing Countries
- Lack of clean drinking water
- Intelligent but have only elementary levels of education
- Solar energy is abundant in most areas
- Clean water is highly valued
- The taste of chemicals within water is disliked
- Low levels of income
- Use water for cleaning, bathing, drinking and cooking
- Lack of ability to maintain/repair system

Customer Needs

Quality of Water
- Water must be within the standards set by the World Health Organization (WHO) to allow for safe use (drinking).
- Water treated using chemicals is disliked by the people of rural communities because of taste. Therefore, microbe contamination must be removed via another method.

Requirements of the System
- Design of the system must take into account the source of water to guarantee successful removal of contaminants.
- Must take advantage of readily available energy (solar).
- Output of clean water must be proportional to the population the system needs to support.
- Ideal life expectancy of a system should be around 50 years but more realistically 10-20 years is the typical lifespan of current systems.

Human-System Interface
- System must be very easy to operate
- Maintenance of the system needs to be relatively simple
- System would most likely need to be serviced by a third party.
- Education and personal training of the system to locals is vital to the overall success of the system from an operational and social viewpoint.

2.2 System Concept and Sketch

The system acts similarly to that of the water cycle: water evaporates in one area (leaving contaminants behind) and condenses as clean water in another area. A simple schematic can be seen in Figure 1. Because this project is intended for coastal communities, an abundant supply of brine water should be readily available. While not in use, the solar troughs should be covered or sheltered from direct sunlight. Protecting the troughs from the sun is important because, if left in direct sunlight while the system is not operating, the heat transfer fluid (HTF) along the length of the troughs will continue to pick up heat, potentially reaching temperatures that begin to damage system components. The insulation had the lowest temperature rating of 120 °C, and therefore was the maximum temperature the system could reach.

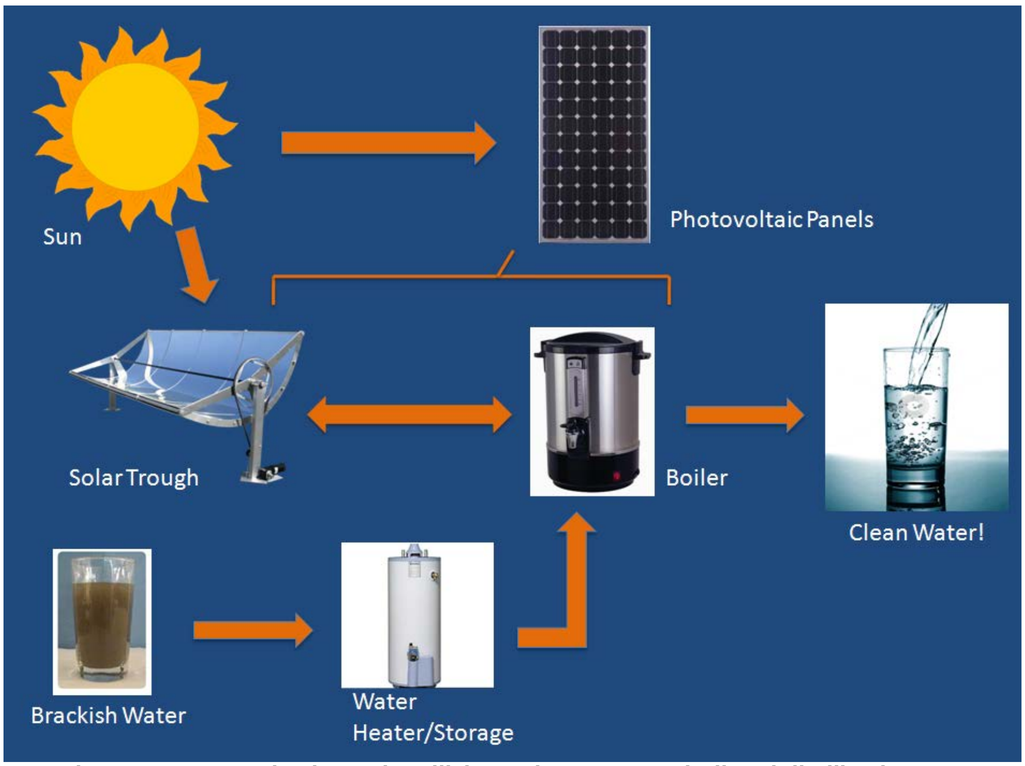

Figure 1: A general schematic utilizing solar energy to boil and distill salt water

At system start-up, the saltwater, originally stored in the saltwater storage tank, flows into the boiler, filling it just above the level of the heat exchanger (HEX). Two float switches located inside the boiler control the opening and closing of a solenoid valve (controlling the flow of salt water into the boiler). A combination of two float switches and a solenoid valve maintain the water level in the boiler, preventing the boiler from overflowing or running dry.

Within the hot loop of the system, a specifically chosen HTF, known as Duratherm-450, circulates through the troughs, picking up energy from the concentrated solar power. The fluid then flows through the HEX inside the boiler, giving off the energy as heat to the salt water. As the salt water reaches the target temperature of 100°C, it boils and causes a vapor pump to switch on. The vapor pump pulls the newly formed water vapor from the boiler, directing it to a helical coil condenser located inside the salt-water storage tank. Heat will leave the condensing vapor to preheat the salt water in the salt-water storage tank. The condensed vapor liquefies and is collected in a clean water storage tank. The overall concept is based on the 2010-2011 Team Clean Water's design. However, the new design incorporates changes that are expected to improve the system's efficiency.

2.3 Functional Analysis

2.3.1 Functional Decomposition

The Solar-Powered Water Purification System functions to remove chemical and microbial impurities from salt water through the use of solar energy. The use of sustainable energy sources creates an environmentally friendly and self-contained system that can be used in a wide range of locations. The system itself is comprised of seven main sub-components: solar collector, HEX, salt-water storage tank, clean water storage tank, boiler, condenser, and system pumps.

Solar thermal collection is accomplished through the use of two custom-built solar troughs. These troughs use a parabolic mirror to focus sunlight on the focal length of the trough. The focused sunlight heats a HTF, which is simultaneously pumped through the system's hot loop and into the boiler. The heat is transferred from the hot loop to the salt water in the boiler through the use of a helical coil configuration HEX. This heat transfer allows for the salt water to reach boiling and begin the evaporation process.

The saltwater storage tank and clean water storage tank function as reservoirs for the salt-water and clean water, respectively; the tanks eliminate the need of constant refilling or emptying. The saltwater storage tank feeds a supply of water into the boiler of the system. The boiler is a vessel in which distillation occurs. Saltwater is heated to boiling temperatures that cause it to evaporate within the boiler. The water vapor is then pulled into a condenser. The condenser is a helical tube located inside the salt-water storage tank. The cold saltwater within the saltwater storage tank cools the hot water vapor. This causes the vapor to condense into liquid that is collected in the clean water storage tank. The condenser also serves to preheat the saltwater entering the boiler, minimizing heat loss and increasing the overall efficiency of the system.

The flow of fluids throughout the system is made possible through the use of system pumps. A vapor pump is used to pull the water vapor from the boiler through the condenser. A HTF pump is used to circulate the HTF through the solar thermal collection loop. The two pumps are powered through the use of a PV panel.

2.3.2 Input and Outputs

The system has two inputs: salt water, and solar energy (in both thermal and electrical form). The source of the salt water was assumed to be 35,000 ppm, which is a typical salinity level for the ocean [1]. It enters the system from the saltwater storage tank to be boiled. Solar energy is provided through the sun, and was assumed to be 850 W/m^2. By utilizing the sun for thermal and electrical power, the system's energy requirements are fulfilled and allow for a completely sustainable design.

The system has two outputs: clean water, and thermal energy. The clean water is obtained through the condensation of water vapor through the condenser. There is an abundance of thermal energy carried within the water vapor as it leaves the boiler. Therefore, by placing the condenser in the salt water storage tank, a preheating process can occur. The heat is transferred from the vapor to the salt water before it enters the boiler. Although some thermal energy is lost to the environment, this was minimized using insulation.

2.4 Benchmarking Results

In order to better understand the key features that need to be applied to the system, three commercially available systems were researched and analyzed. It was found that each of the three systems possessed valuable features; however, they also lacked other important aspects. By integrating characteristics of these three systems, this year's team will create a revolutionary Solar-Powered Water Purification System.

2.4.1 SwissINSO Holdings, Inc.'s Krystall

The Krystall, by SwissINSO Holdings, Inc., is a patented reverse osmosis and membrane filter system, consisting of two standard 40-foot shipping containers (Figure 2). Water is pretreated by the unique membrane filter system (a sand filter and a secondary filter) before it is treated by reverse osmosis. High performance PV panels power the Krystall, and a battery bank stores excess energy that can be used when there is no sun. Additionally, a diesel back-up generator powers the system during extended periods with little or no sun. This fully autonomous system is completely off the grid and uses no chemicals. Although the system is able to produce up to 98,421 liters (26,000 gallons) of purified water per day, the system is bulky, immobile, and it comes at a price tag of $1,200,000. The system cost is extremely high and is unrealistic for developing countries with limited funds. Based on a ten-year life span, the cost per liter of the Krystall system is $0.003/liter. Although the cost is very low, a large initial payment must be made. In addition, the price indicated does not include the start-up cost, maintenance, the cost of diesel or the cost of replacement filters. Another major downfall of the system is that the filters need to be changed out once every 4-5 years, which is problematic as education is limited in developing countries.

Figure 2: Representation of the Krystall by SwissINSO Holdings, Inc.
(http://www.swissinso.com/products/krystall.html)

2.4.2 Trident Device's H2All Mobile

H2All Mobile, by Trident Device, is a hybrid system that utilizes standard, ultra, and nano-filtration to purify water (Figure 3). This system is capable of removing salt, dirt, silt, bacteria, cysts, parasites, viruses, and other contaminants using this multi-stage process. A photovoltaic panel supports all of the system's electrical needs, taking the H2ALL Mobile completely off the grid. The H2ALL Mobile system also incorporates a collapsible, 2,500-gallon bladder-type storage tank that makes its easily portable. The system's heavy-duty wheels enable it withstand the harshest elements and terrains. For $9,000, the H2ALL Mobile system can purify up to 567 liters (150 gallons) per day. Based on a ten-year life span, the H2All Mobile costs $0.004 per liter of purified water. However, even though the system is portable and efficient, it has many sophisticated filters that require changing.

Figure 3: Representation of H2All Mobile by Trident Device (http://www.tridentdevices.com/mobile-solar-water-purification-systems/)

2.4.3 Epiphany's E3 Direct Solar Distillation System

Epiphany's E3 Direct Solar Distillation System utilizes the power of concentrated sunlight through its parabolic dish shape (Figure 4). The intense heat created by this set-up immediately vaporizes the contaminated water, removing dissolved solids and living organisms. The vapor is then condensed; and the resulting water is deemed safe to drink. E3 is lightweight and the installation time is designed to be less than one hour, regardless of the skill level of the person. At $25,000, the E3 Direct Solar Distillation System is able to produce 379 liters (100 gallons) of clean water per day using only solar power. Even though the system uses desalination (rather than filtration and reverse osmosis), the system is largely stationary once it is assembled. Factoring in a 10-year life span, the cost per liter is $0.018/liter, which is more expensive than both the Krystall and the H2All Mobile.

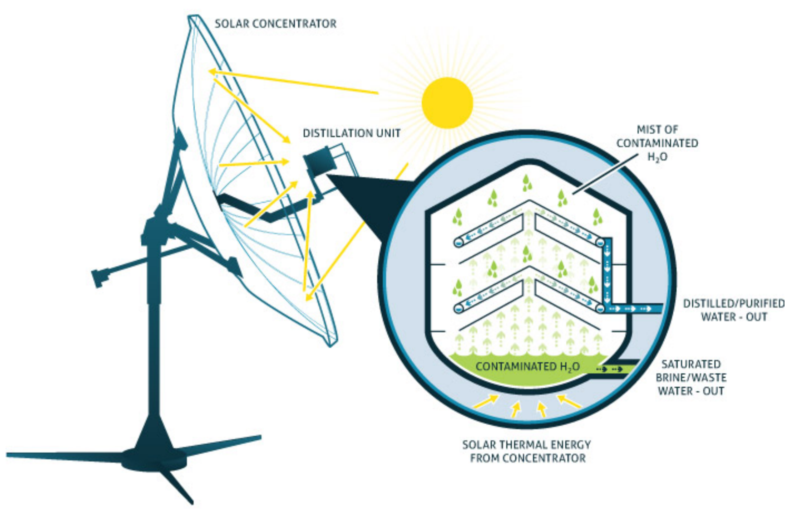

Figure 4: Representation of E3 Direct Solar Distillation System by Epiphany (http://epiphanysws.com/technology/)

2.4.4 System Comparison

Table 2 summarizes the key features of all three systems described previously. Even though Krystall and H2ALL Mobile are capable of producing a lot of clean water per day, they require that filters that need to be changed on a regular basis. Not only will the people in developing countries have difficulty obtaining and affording the replacement filters, but also they may not know how to change the filters. The year's team aims to design a system that is portable and requires little to no maintenance. In addition, the system can be easily shipped and will have a large water output for the price of the system. Although the system has a small water output, it is scalable, allowing for a larger water output with a small economic impact.

Table 2: Comparison between three water purification systems and this year's Solar-Powered Water Purification System

	Krystall	H2All Mobile	E3 Direct Solar Distillation	2011-2012 Solar-Powered Water Purification System
Type of System	Filtration/Reverse Osmosis	Filtration	Desalination	Desalination
Water Output (liters/day)	Up to 98,421	Up to 567	379	30
Cost	$1,200,000	$9,000	$25,000	$5,000
Cost per Liter ($/liter)	$0.003	$0.004	$0.018	$0.046
Dimensions of System	7.5'x8'x40' (per shipping container)	5'x3'7"x7'8"	15'x15'x11'	Capable of fitting in a single shipping container
Off-Grid?	Yes	Yes	Yes	Yes
Portable?	No	Yes	No	Yes

2.5 Key System Level Issues and Constraints

The team is facing the challenge of providing a source of clean water for communities in which many resources are not readily available; therefore, care was taken in using easily obtainable materials. In designing a system that is capable of purifying contaminated or saline water, the team had to take into account the size, portability, durability, ease of use, and the costs that are associated with it. Multiple subcomponent designs and functions were analyzed using Concept Scoring and Prioritizing Matrices, Appendices H and K, respectively. These design constraints must be accounted for in producing such a system in order for it to be considered economically viable.

2.6 Layout of System Level Design with Main Subsystems

Figure 5 shows the system level design, depicting the major subsystems, inputs, and outputs. As seen in the diagram below, there are four main paths: red denoting the solar loop/hot loop path, brown showing the salt water path, blue outlining the water vapor/clean water path, and green showing the solar electric paths. The solar loop runs through the troughs, collecting concentrated heat from the sun. The HTF within this loop then runs through a HEX, located just under the surface of the salt water in the boiler. The stored energy in the HTF will provide the heat necessary for boiling and distillation to occur within the system. Once the heat is transferred into the boiler, the loop is then completed as the HTF goes around and reabsorbs energy from the solar collectors. The salt-water path runs directly from the salt-water storage tank to the boiler, utilizing gravity and a solenoid valve to control the flow and level of the salt water inside the boiler. Two float switches within the boiler will regulate the maximum amount of salt water inside; in addition, a one-way check valve is used to ensure one directional flow. As heat transfers to the salt water, evaporation begins to occur. A vapor pump, located immediately after the boiler, pulls the newly formed water vapor out of the boiler and pushes the vapor through a condenser. After condensation, the clean water is deposited into the clean water storage tank; the water vapor/clean water path depicts this. The helical coil condenser is placed within the salt-water storage tank to facilitate condensation and to preheat the salt water. The cold salt water will absorb the heat from the hot vapor in the condenser, causing the vapor to condense back into liquid water while also slightly heating the salt water before it goes to the boiler to be further heated. In order to remove the system from the electrical grid, a PV panel is added to power the various pumps incorporated into our design. The green paths show the electrical wiring needed for our system.

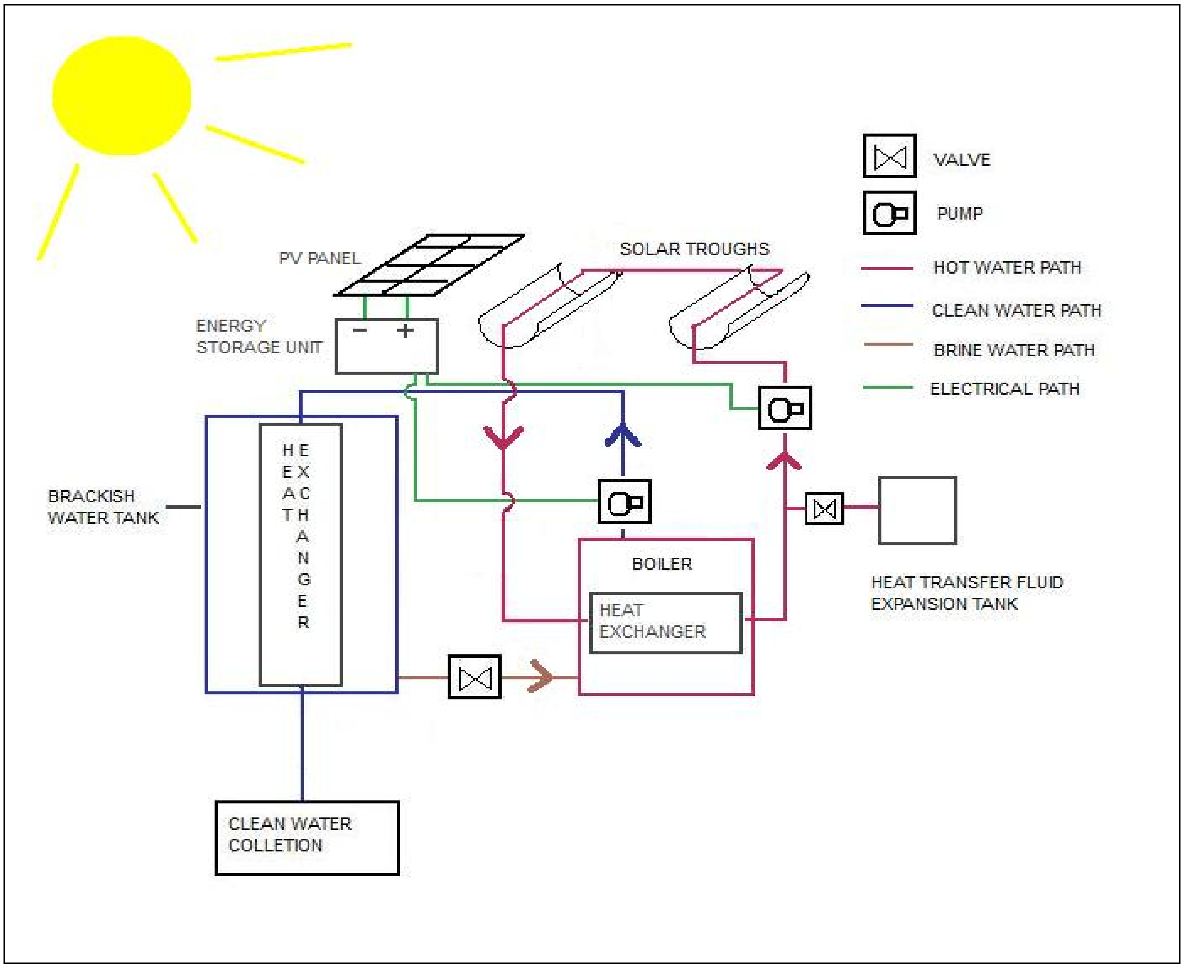

Figure 5: Block diagram of major subsystems of the design

2.7 Team and Project Management

2.7.1 Project Challenges and Solutions

The primary challenges for this project was completing tasks by their deadlines, as well as reaching the target temperature of 100 °C within the boiler. The team was given the task to improve the previous year's system, but, after much discussion, the team decided to create a completely new design. Many hours were spent trying to test and become familiar with the old system, which provided information regarding which components could be reused and which were to be replaced or redesigned. Unfortunately, many main of the components of the existing system, such as the flat plate solar collector, the vacuum pump, the vapor pump, and the condenser were ultimately removed from the system. The extent of efforts used to analyze the system, as well as extent of redesign of the overall system was much greater than anticipated. Therefore, the team had a late start in designing the new system. To return on schedule, the team worked through weekends and holidays to build the system. Also additional delays occurred during construction. For example, copper parts would become deformed during soldering, and the solar tracker would malfunction. To address these problems, additional tasks would be assigned as necessary to find efficient and cost effective solutions. Due to these unanticipated delays, the team did not get to do as much testing and make as many modifications as anticipated desired Initial testing showed that the system could not heat the salt water up to 100 °C, even when left out for six to eight hours. With only three weeks available for testing and modifications, there was insufficient time to make extensive changes to the design. However, the team was able to make minor changes, such as improving the focal length of the troughs, adding a convective envelope, and testing a new flow rate. Enough tests were conducted to draw conclusions regarding the impact of changes on the system performance, and are further discussed in Section 5. Completing tasks by deadlines was a challenge due to unexpected hurdles, but the team still managed to do a great job to complete main goals on time.

2.7.2 Budget

The team requested the max amount of $3,000 from the CSTS Grant Program and $3,000 from the Dean’s Engineering Undergraduate Programs Senior Design Funding. From these requisitions, the team received a total of $6,000 as seen in Appendix N.

The only equipment the team had were the remnants of the previous year’s design project. Therefore, the money received from the CSTS and Dean’s Funding went directly to purchasing new parts and components that were deemed necessary to the progress of the system. The team acquired a few external partners/supporters such as Duratherm, whose donation of the HTF partially reduced the overall cost of the system.

2.7.3 Timeline

In order to ensure successful and on-time completion of all goals, a Gantt chart (Appendix M) was created. Included in the Gantt chart are weekly group meetings, advisor meetings, major course assignment deadlines, and subcomponent tasks. The team progress was compared to the Gantt chart each week to make sure that the team was keeping on task.

Fall quarter was devoted to designing the concept for the system. The first step was to familiarize the team with the system that had been passed on from the previous year. In addition, interviews were conducted to identify customer needs. Simultaneously, an Engineering Equation Solver (EES) model was created in order to determine which portions of the previous system should be kept and which portions should be revised and replaced. A basic conceptual design was then developed.

During the winter quarter, the team focused on finalizing details of the design. The final design was chosen based on research of the best solutions and the EES model. Much of the time was devoted to researching components that were compatible for the system and easily obtainable. The parts were then ordered, and assembly of the system began. A rough prototype was completed by the end of the quarter. The system was also modeled in SolidWorks.

In the spring quarter, the assembly of the system was fully completed. Testing then began on the system and analysis was performed to determine possible revisions. Changes were made to improve the system and further tests were conducted. All adjustments were made in time for the Senior Design Conference on Thursday, May 10, 2012. The remainder of the quarter was devoted to working on the thesis, which was due on June 16, 2012.

2.7.4 Design Process

For the success of all design projects, a process must be established. The process ensures a directional flow towards completion and establishes a basic time and progressing framework. The team broke the process into general segments, starting with research and information gathering, engineering design, design implementation, and testing and re-fabrication. Each segment loosely correlated to the academic school year: summer, fall, winter and spring quarter.

During the spring quarter of 2011, six peers decided to follow up on Team Clean Water's Solar Water Purification System. Thus, the Solar-Powered Water Purification System team was formed for the 2011-2012 Senior Design Challenge. The summer was completely devoted to diving into research on the current system, as well as other similar designs in order to completely understand the processes included in the design. More research and understanding would lead to a better grasp on the subject matter (solar distillation, thermodynamics, fluid mechanics, etc.) as well as provide knowledge on today's most efficient, most innovative engineering solutions. Relevant documents, articles, theses, etc., were collected and distributed amongst the team members via email and Facebook (Senior Design Group). This allowed each member to be completely up-to-date with every other member in terms of what had been researched as well as specific updates regarding the project.

The fall quarter of 2011 marked the “engineering design” phase in which the team took the gathered information and used it to analyze and test the previous year’s system’s physical operations. Based on how the system actually functioned, compared to the research and the previous team’s thesis, a more concrete design plan was laid out. A Gantt Chart was developed to frame the project’s timeline. In addition, a comprehensive budget was created; it included the cost of all components necessary to complete the project. Building off the summer’s research, the team proposed a completely new design to create a better solar-powered water purification system than the previous years. The new design was tested by modeling it in the EES software and then further finalized with corresponding dimensions and details.

The new design modeling led into the winter quarter. As the design was further being developed, the design implementation started. This quarter was reserved for procuring materials and various components to create the system. During the spring 2012 quarter, building had begun and many hours were spent in the machine shop to build the complete system by the specified deadline. The system was completed a few weeks before the Design Conference in the spring quarter. A few weeks were spent testing the system and making modifications and improvements before the conference.

2.7.5 Risks and Mitigations

One of the main risks for this project is the weather. The system was designed to operate during a sunny day with an average solar irradiance of 850 W/m^2. The system can only run in sunny conditions; therefore, the system was designed for coastal communities with abundant sunlight.

Another risk involved with the project would be contaminants and high salinity in the water. We must be able to guarantee that the dangerous contaminants are removed and the water is safe to drink and use. By boiling the salt water, the system will remove all contaminants, making the condensed vapor safe to drink.

2.7.6 Team Management

The Solar-Powered Water Purification team designated Andrew Nosé as the team leader, Alex Tamai as the facilitator, and Christopher Sugii as treasurer; but all team members were accountable for doing an equal amount of work. In order to maximize team efficiency and ensure accountability, subcomponent groups were created accordingly:

- Solar Troughs/PV Panel – Andrew, Reece, Erin, Chris
- Controls – Reece, Chris
- EES/Pumps – Alina, Alex
- Boiler/HEX/Condenser/Clean Tank – Alina, Alex, Andrew
- Piping/Foundation – Chris, Andrew, Erin

The subcomponent groups allowed for different options to be simultaneously explored for all the components. Members of the subcomponent groups were the experts in that field and would provide any information that others needed.

The team primarily communicated through phone, email, Facebook, Angel/Camino, and weekly meetings. All members often talked directly or checked their messages for close and open communication. It was important that all group members maintained good communication in order to complete tasks and to stay on schedule. All members had very different schedules, so maintaining an open line of communication and completing work in subcomponent groups was a major factor in accomplishing goals.

Section 3: Mechanical Subsystems

The mechanical subsystems of the Solar-Powered Water Purification System consisted of a boiler, solar collectors, drive system, HTF, boiler HEX, condenser, and HTF and vapor pumps. The boiler contained the salt water, allowing for it to boil and distill. The energy for boiling was provided by the solar collectors, which concentrated the energy from the sun. The drive system allowed for the collectors to maximize the solar input by tracking the sun. The HTF absorbed the solar energy as it flowed through the collector, and transferred the energy to the salt water via the boiler HEX. As the salt water evaporated, the vapor travelled through the condenser to return to the liquid phase for containment. The HTF and vapor pumps motivated the flow of the HTF and vapor, respectively. The operation of these mechanical systems were connected, and had to operate together in order for the distillation process to occur successfully.

3.1 Boiler

The distillation process for the Solar-Powered Water Purification System happens in the boiler. The salt water vaporizes when the water within the boiler is boiled from the heat provided by the hot loop. The hot loop uses a HTF that collects heat from the solar parabolic troughs. That HTF runs through a HEX in the boiler and transfers the heat to the salt water. This causes the water to boil and separates water vapor from undrinkable debris and contaminants. All the contaminants and other waste in the salt water are killed at atmospheric pressure because of the boiling process. After the vapor leaves the boiler, it is then condensed into purified drinking water.

Many designs were considered for a new boiler. The team looked into using a high-heat plastic material for the boiler to prevent corrosion, but it was discovered that making modifications would be too complicated and expensive. A square shaped boiler was also sought for to make easier connections, but in the end nothing could be found that would fit the needs in the price range. So, the team decided to use the previous year's boiler, which is an All-American industrial size aluminum pressure cooker. This container has a wall thickness of .635 cm, and can hold 38 liters of water. Figure 6 depicts a SolidWorks model, as well as the actual boiler used in the system. This boiler previously had corrosion problems, so it was anodized to prevent the aluminum from corroding. High heat plastic nipples were also used to connect dissimilar metals to further prevent corrosion. After construction, approximately 2.54 cm of insulation was wrapped around the boiler to minimize heat loss to the environment.

(a) (b)

Figure 6: SolidWorks model of boiler and actual insulated boiler

From the experimental data, the most promising test on 5/8/2012 showed that with an average of approximately 0.56 kW input into the boiler and an initial temperature of 26.5 °C, it took four hours for 0.023 m^3 (23 liters) of water to reach 95 degrees Celsius. To obtain this temperature rise for water requires a total heat input, Q_w, of 6.56 kJ:

$$Q_w = (V_w)(\rho_w)(C_{p,w})(\Delta T_w) = (.023)(1000)(4.18)(95 - 26.5) = 6{,}586\ kj \quad (1)$$

Where V is the volume, ρ is the density, C_p is the specific heat, and ΔT is the temperature rise. The subscript W denotes water because all tests were done using water rather than salt water. The input to the boiler, Q_{boiler}, was 8,064 kJ:

$$Q_{boiler} = Q * time = 0.56 * 3600 = 8{,}064\ kj \quad (2)$$

Based on this, the losses of the boiler, Q_{loss}, and the efficiency of the boiler, η_{boiler}, were quantified to be 1478 kJ and 81.7%, respectively, over the 4 hour operation period.

$$Q_{loss} = Q_{boiler} - Q_w$$
$$H_{boiler} = 100\left(\frac{Q_w}{Q_{boiler}}\right) \quad (3)$$

Although there were some losses, an efficiency of 81.7% is quite high. Therefore, the insulation was considered sufficient for the system. For future improvements the team would suggest using a smaller boiler that has less thermal mass, so that time to heat up would not be as high. In addition, design changes to accommodate easy drainage would be desired. Detailed drawings can be seen in Appendix B.

3.2 Solar Collectors

The solar collectors (solar parabolic troughs) function as the system's solar thermal energy-harnessing source. The largest advantage of a solar parabolic trough over other methods is its ability to concentrate the energy from the sun to yield higher energy collection efficiency for a low cost. The basic design of the solar parabolic troughs was inspired from George Plhak's manual [11]. Although this provided a foundation of where to begin, research was conducted to determine the materials that should be used and to verify the design. A major material of the solar parabolic trough is the reflective surface. The team chose to use an acrylic material, measuring 2' by 8' by 0.062" for each of the solar parabolic troughs.

The performance of the solar parabolic trough is also based on the energy from the sun. The fluctuation of the energy varies greatly depending on location, season, and even throughout any given day. Therefore, the model created with EES does not cover every scenario; however, it considers an average day where the energy flux received from the sun is 850 W/m^2. In order to evaluate the EES model, the system's performance was rated based on how close the energy received from the sun matched the energy needed to reach a designated change in temperature. The change in temperature desired corresponds with the difference between the inlet temperature (into the first trough) and outlet temperature (from the second trough). Some materials and properties were held constant throughout the modeling process. The collector tube was assumed to be copper and the heat transfer fluid (HTF) was assumed to be water in initial calculations.

The net energy from the sun was calculated first. The total amount of energy received from the sun is based on the energy flux and the area receiving that energy. Here, an assumption was made that the area receiving the energy was a flat rectangular surface (rather than a parabolic shape). In an ideal case, all of this energy would transfer to the HTF; yet, that is not the case in real world applications. There are energy losses due to radiation, convection, and conduction. The EES model disregards conduction because the pipe thickness is fairly thin; so the assumption can be made that conduction will yield minimal losses. As such, the main contributors to energy loss were assumed to be from radiation and convection.

In calculating the energy loss due to radiation, a few assumptions were made. The emissivity of the collector is assumed to be one. This implies that the collector tube absorbs all energy, rather than reflects it. Since the collector tube used in the team's trough is painted black, this is a fair assumption. In addition, the temperature of the HTF (and corresponding properties) was taken at an average between the inlet and outlet temperatures of the troughs (80°C and 90°C, respectively). Calculating the convective energy losses to the surroundings assumed the same conditions above with one extra condition. The ambient air temperature and pressure at which the properties were evaluated at were assumed to be 30°C and 100 kPa, respectively.

Based on the method and assumptions described above, the EES model was created and tested to find areas that could be modified for better efficiency. Failure in this situation was considered as any situation where the energy transferred to the HTF was much less than the energy received from the sun. This would mean that the model was either inaccurate, or materials and conditions were not optimized.

The EES model could be compared to simple hand calculations that make many basic assumptions. It is important to note that the equations from both methods match, and would therefore yield the same results. The major difference is that EES gives the user the ability to test variables quickly and efficiently through the use of parametric tables. Therefore, the results of the EES model can be better examined and modified better through testing data. In the meantime, it gave general guidance with design decisions and when to expect failure.

To determine the mode of failure, the model was evaluated and tests were done to yield better results. For example, the relationship between the diameter of the collector tube and the heat received by the HTF was evaluated before the tube was purchased. Since the cost increases with the diameter, the economical thing would be to purchase a small diameter; however, the effect on the system needed to be evaluated. This was determined by creating a parametric table with diameters ranging from 0-0.099 m. As is evident in Figure 7, the net energy into the trough decreased as the diameter of the collector tube increased. Even though smaller diameters would be ideal, there is a tradeoff to consider. Larger diameters are ideal when considering the minor imperfections in the focal line of the solar parabolic trough. A larger surface area allows increases the focal area. After determining the tradeoffs, it was determined that 2.54 cm (or 1 in) would be an ideal diameter.

Discussed in Section 3.4.2, the Solar Collector EES model was used in conjunction with the HEX EES model to identify a target HTF flow rate through the hot loop.

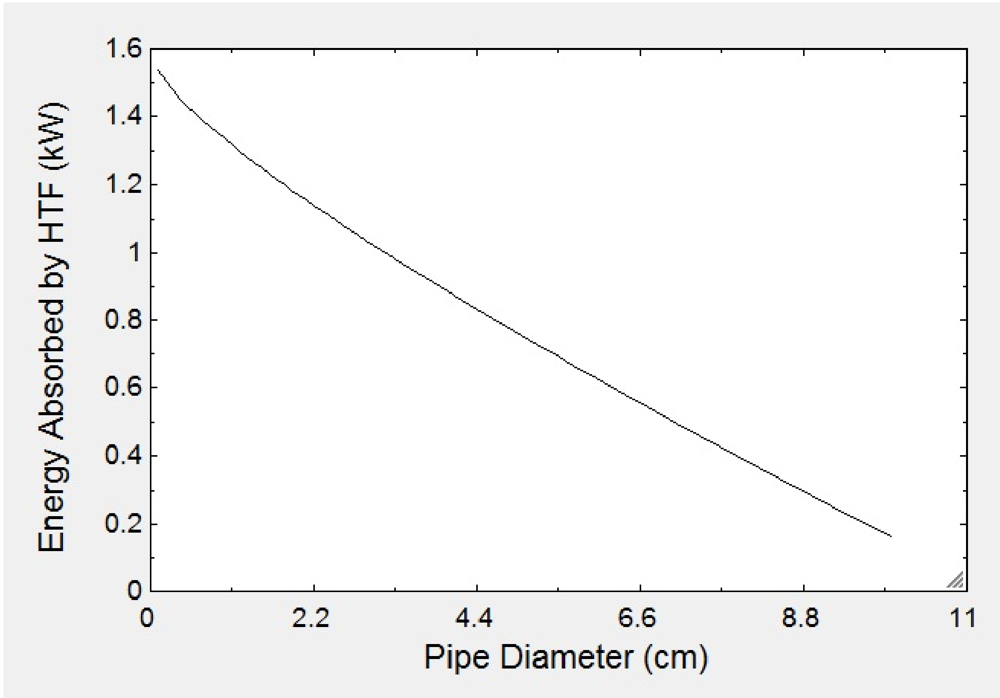

Figure 7: Relationship between energy absorbed by the HTF and pipe diameter

3.3 Drive System

A drive system was employed to facilitate the movement of the two solar collectors and PV panel. This single axis rotation is necessary in order to accurately track the sun's movement across the horizon throughout the day. A 15 W drive screw motor, rotating at 6 RPM, was employed to power the rotation of the solar collectors. The motor's direction of movement was controlled by a differential light sensor and an Arduino microcontroller (see Section 4). These two components provided the logic necessary for the accurate operation of the drive screw motor throughout the course of any given day.

3.4 Heat Exchangers

3.4.1 Heat Transfer Fluid (HTF)

The HTF absorbs heat as it flows through the troughs and transfers this heat to HEX located in the boiler. A single-phase flow was desired to avoid pressure changes that would quickly lead to leaks within the piping, as well as reduced heat transfer capabilities of the fluid. Salt water boils at approximately 100°C, so the HTF must be in a liquid phase above that temperature to transfer heat in the HEX. Three main fluids were considered: water, glycol, and an oil-based fluid. Water is considered an ideal HTF because of its low maintenance, cost, and environmental impact. However, it boils at 100°C and, therefore, a single-phase flow would not be maintained. Glycol is a water-sugar mixture that can reach higher boiling temperatures at certain concentrations. It also has a low environmental impact because it is biodegradable. However, it requires extensive maintenance, as sugar levels must be regularly monitored. Ultimately, an oil-based fluid called Duratherm-450 was selected. It has a boiling point of 232°C and requires low maintenance due to additives, including antioxidants, corrosion inhibitors, de-foaming agents, seal and gasket extenders, suspension agents, and metal deactivators. Although it has a moderate environmental impact, and must be disposed of with other waste oils, it is not considered toxic and does not cause skin irritation when accidental contact occurs. A summary of the three fluids and their properties are provided in Table 3.

Table 3: Properties of HTF options

Type of Fluid	Boiling Point (°C)	Maintenance Level	Environmental Impact
Water	100	Low	None
Glycol	102-188	High	Low (Biodegradable)
Duratherm-450	232	Low	Medium (Dispose with waste oils)

3.4.2 Boiler Heat Exchanger (HEX)

A HEX was located within the boiler, and allowed for transfer of energy from the HTF to the salt water for boiling. To maximize the surface area for heat transfer, and guided by the boiler dimensions, the HEX was designed to be a helical shape. Therefore, the major design variables to select were the tube diameter, number of coils, and HTF flow rate. To appropriately size these parameters, a HEX model was developed in EES. A resistance circuit was set up for heat transfer during the nucleate boiling regime, which was the target regime of our system, and is shown below in Figure 8.

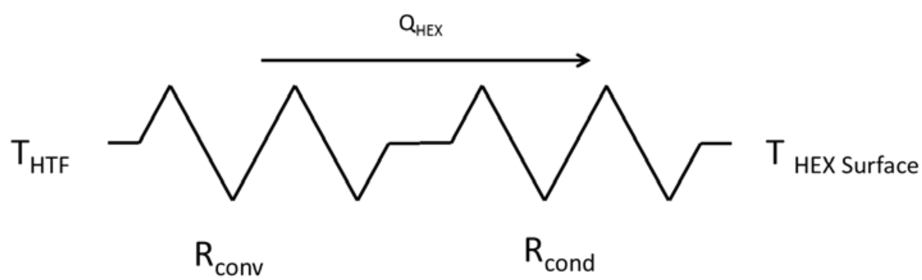

Figure 8: Resistance circuit of the HEX

A resistance associated with boiling was difficult to find, so resistance due to conduction, R_{cond}, and convection, R_{conv}, were used to calculate a heat flux across the HEX to its surface by the equation:

$$Q_{HEX} = \frac{T_{HTF} - T_{HEX,surface}}{R_{cond} - R_{conv}} \tag{4}$$

where Q_{HEX} is the energy transferred through the heat exchanger, T_{HTF} is the average temperature of the heat transfer fluid through the HEX, and $T_{HEX,surface}$ is the surface temperature of the HEX. An energy balance was used based on this heat flux to equate the energy transferred to the salt water assuming nucleate boiling through the equation [12]:

$$Q_{HEX} = \mu_l h_{fg} \sqrt{\frac{g(\rho_l - \rho_{v)}}{\sigma}} \left(\frac{c_{p,l} \Delta T_e}{c_{s,f} h_{fg} Pn_l^n} \div \right)^3 * A_{S,HEX} \tag{5}$$

Where μ_l is viscosity, h_{fg} is the enthalpy of vaporization, ρ is density, σ is surface tension, C_p is the specific heat, Pr is the Prandtl number, and $A_{S,HEX}$ is the surface area of the HEX. $c_{s,f}$ and n are parameters dependent on the surface-fluid combination and subscripts *v* and *l* denote the saturated liquid and vapor phases, respectively. Finally, ΔT_e is defined at the different between the surface temperature and the fluid's saturation temperature.

$$\Delta T_e = T_{HEX,surface} - T_{sat} \tag{6}$$

In addition, the Q_{HEX} was balanced with the energy lost by the HTF, Q_{HTF} by:

$$Q_{HTF} = \dot{m} C_P (T_{in} - T_{out}) \tag{7}$$

$$Q_{HEX} = Q_{HTF} \tag{8}$$

For the initial model, T_{in} was set to be constant, and the remaining coupled variables were solved for iteratively using EES. The model showed that heat transfer across the HEX decreased as the tube diameter increased. Therefore, a smaller tube diameter was desirable. However, this would negatively impact the static pressure of the system and would force the pump to consume more power. In addition, commercially available products constrained the selection process. With these considerations in mind, 0.95 cm (3/8 in) copper tubing was selected. Copper tubing would also allow easy construction and attachment to the boiler frame.

With the selected diameter, nine coils were selected for the helical shape, which was the maximum number that could fit within the boiler. This number was selected based on considerations of increasing static pressure with increasing coil number as well as maximizing surface area for heat transfer to occur. Although over sizing the HEX could be possible, the model showed this was not the case. With nine coils, the HEX would transfer approximately 2.3 kW while the amount of energy required to evaporate the target amount of vapor is approximately 2.1 kW.

The HEX model was used in conjunction with the Solar Collector model to determine the initial target HTF flow rate. Both models were run individually to see how flow rate impacted heat transfer. As seen in Figure 9, as mass flow rate increased both Q_{trough} and the energy transferred through the HEX (Q_{HEX}) increased. At 0.1 kg/s, Q_{trough} equals Q_{HEX}, and the amount of energy transfer is approximately 2.3 kW. Therefore, 0.1 kg/s was the initial target flow rate of the system for pump selection.

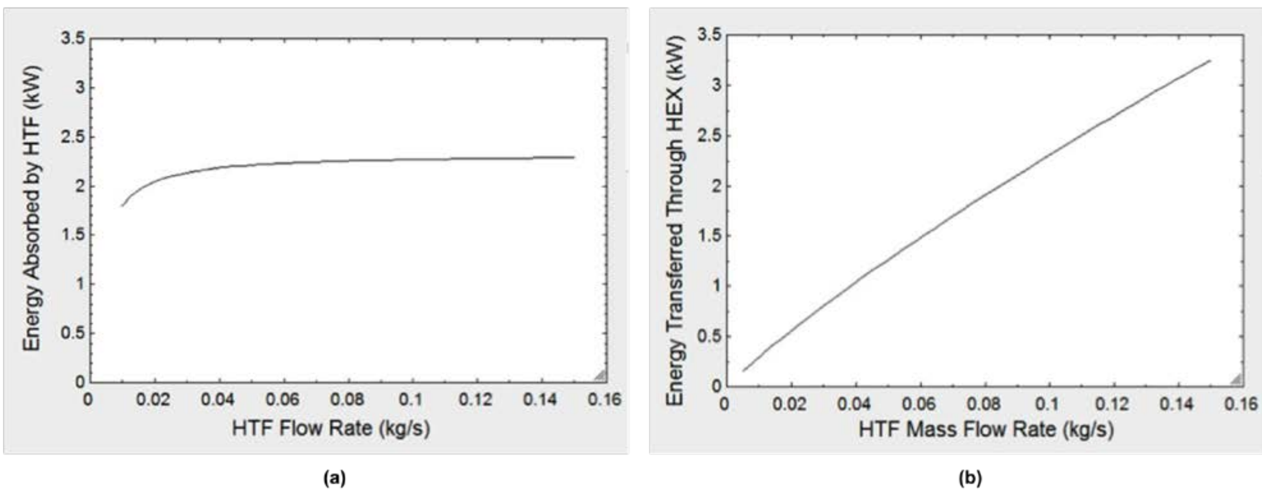

Figure 9: Impact of HTF flow rate on (a) Q_{trough} and (b) Q_{HEX} based on individual models

As the project progressed and as testing was performed, the Solar Collector and HEX models were refined and integrated into one model. The integrated model was run again to see the impact of flow rate on heat transfer, and is shown in Figure 10. Surprisingly, the impact of HTF flow rate was the opposite of what was initially modeled. This was found to be because the assumption of a constant inlet HTF temperature was incorrect. Based on the integrated model, a new target HTF flow rate of 0.015 kg/s was identified for further testing.

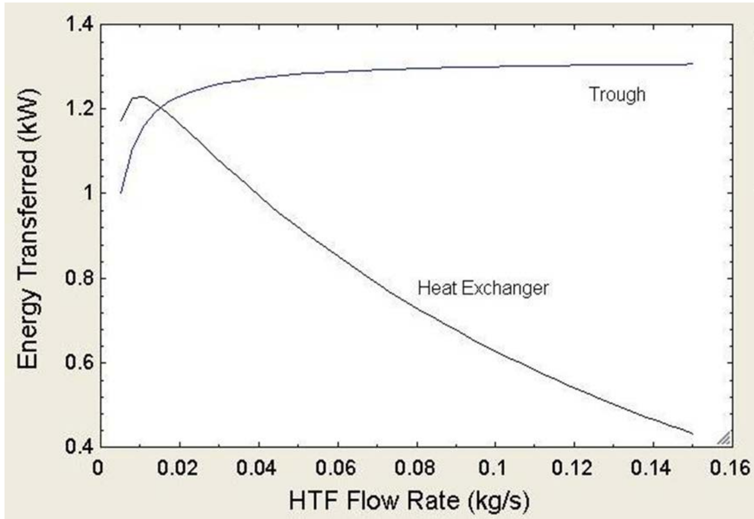

Figure 10: Impact of HTF flow rate of Q_{trough} and Q_{HEX} based on integrated model

3.4.3 Condenser

The condenser was located within the salt-water storage tank and allowed heat transfer from the vapor to the salt water. In doing so, the vapor would change to distilled water while the salt water would be preheated. Again, this was modeled in EES to determine the minimum length to condense the vapor. The amount of heat transfer required (Q_{vapor}) was calculated based on the target vapor flow rate and removal of the latent heat by:

$$Q_{vapor} = \dot{m}_{vapor} h_{fg} \tag{9}$$

Sensible heat transfer from 100°C to 95°C was initially added to the total amount of heat required to be removed by the condenser, but was found to be negligible. Q_{vapor} was balanced with the energy transferred through the condenser, $Q_{condenser}$. This was calculated using the resistance circuit of the condenser, shown in Figure 11.

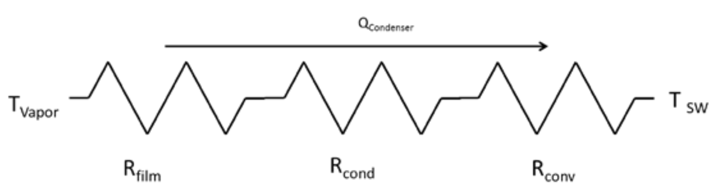

Figure 11: Resistance circuit of the condenser

R_{film} is the resistance due to film condensation on the inner surface of the condenser, and R_{cond} and R_{conv} are the resistances due to conduction and convection, respectively. R_{conv} was assumed to be natural convection of the salt water, which was considered to be stagnant in the storage tank. The calculation for the resistance circuit is:

$$Q_{condenser} = \frac{T_{vapor} - T_{SW}}{R_{flm} + R_{cond} + R_{conv}} \quad (10)$$

$$Q_{vapor} = Q_{condenser} \quad (11)$$

As water is distilled, the water level in the tank would decrease, and, therefore, expose the condenser to air. Therefore, to determine the limits of the condenser length, two cases were considered: first, the condensing fluid was assumed to be air, and secondly, the condensing fluid was assumed to be water. In addition, because the condensing fluid would be heating during system operation and as it was exposed to sunlight, the temperature of the condensing fluid was assumed to be 80°C. Based on these assumptions, the condenser length was calculated to be 200 m for air and 0.1 m for water. It was critical for the condenser to be submerged in water because a 200 m condenser was not feasible.

Based on these calculations, the condenser tube diameter was not critical to heat transfer because an impractical length would still be required if the condensing fluid was only air. Therefore, the 0.95 cm (3/8 in) copper tubing remaining from construction of the HEX was selected as the condenser material. Not only was it readily available, but also it was easy to bend and shape.

3.5 System Pumps

3.5.1 Heat Transfer Fluid (HTF) Pump

The HTF pump drove the circulation of the HTF through the hot loop, and was selected based on various criteria, of which the main ones were: overcoming the static pressure of the loop while providing the initial target flow rate of 0.1 kg/s, consuming a maximum of 80 W of DC power, and compatibility with the HTF. Based on the length of copper piping in the system and number of bends, the static pressure of the system was calculated to be 80 kPa. From the solar panel capacity of 120 W of DC power, the amount of power budgeted to the pump was 80 W and was constrained to DC power. This constraint was further justified because an AC/DC converter would decrease efficiency while increasing costs, and DC power would allow for easier adjustments to the flow rate during testing. Based on these design considerations, an Oberdorfer N991-32 Series Gear Pump was selected. This pump has Viton seals, which are compatible with the HTF. This pump also has a temperature rating of 150°C, and was placed at the inlet to the solar collectors. Thus, the pump was exposed to the HTF at its coolest point, minimizing the possibility of overheating.

3.5.2 Vapor Pump

The vapor pump drove the vapor out of the boiler and into the condenser. The main criteria for selection of this pump included its capacity, ability to run wet and dry, and a maximum power consumption of 15 W. The goal of the system was to provide 1.05×10^{-6} m^3/s (1 gal/hr) of vapor, and therefore the pump was required to pull at least that amount of vapor. In addition, because control of the vapor pump may require it to run when no vapor is present, the pump was required to be able to run dry without failing. Finally, due to the solar panel capacity, the 15 W power constraint was included. Based on these design considerations, a Greylor RF-100 Peristaltic pump was selected. The pump had a temperature rating of 120°C, and was placed at the highest point between the top of the boiler and the inlet to the condenser. This allowed for optimal performance of the pump, as recommended by the manufacturer.

3.6 Piping and Foundation

Piping within the system was conducted using standard 2.54 cm (1 in) copper piping, and soldered together using a lead-free solder material. The design of the piping was conducted in a logical fashion, and many break points along the length of the piping were created to allow for quick removal and replacement of damaged or faulty piping/fittings. This modular design was specifically intended to expedite the maintenance process. A number of valves were also included which allow for the bypassing of the solenoid valve into the boiler for testing purposes or for manual operation of the in-flow to the boiler. A drain valve was implemented at the exit of the solar trough line to allow for the quick removal of heat transfer fluid when maintenance and replacement is required. A number of nylon fittings were attached to the boiler to separate dissimilar metals from each other, reducing the risk of galvanic corrosion to these otherwise vulnerable areas.

The foundation was constructed using standard 0.64 cm (¼ in) thick plywood boards for the base and 1.27 and 2.54 cm (½ and 1 in, respectively) thick wood beams for the solar collector mount. The beams were attached to the foundation using steel brackets and wood screw fasteners. A cross beam was added on each side of the solar collector mount to increase its strength and resistance to torsional forces. The foundation was then coated with two layers of polyurethane to protect it against liquids and oils that it would be commonly exposed to by the system and the environment.

Section 4: Electrical Subsystem

4.1 Overview

The purpose of the electrical and control system is to power and control the actions of the system components. This includes the HTF pump, vapor pump, solenoid valve, cooling fan, and the solar tracker. A microcontroller will be used to obtain ambient light readings, boiler water level, and boiler temperature. These measurements are used to optimize system performance by providing data that will be useful to evaluate system ramp up time and overall power consumption. An external pulse width modulation motor driver from Cana Kit will be used to control the speed of the HTF pump; and a solar tracking controller from Spelling Business Enterprises, LLC will be used to control the tracking system motor.

4.2 Hardware

The control system performs three functions: Input/Output (I/O), Signal Conditioning, and Signal Processing. A breadboard integrates the cadmium sulfide photoresistors, an Adafruit Industries thermocouple amplifier breakout board, and a liquid crystal display. The main processing functions of the control system are performed by the Arduino Mega 2560 microcontroller board based on the ATmega2560 integrated circuit chip. Power switching is accomplished through the use of electromechanical relays driven by switching transistors that control the operation of a solenoid valve, geared motor, vapor pump, and HTF pump.

4.3 Input/Output

The output pins on the Arduino Mega 2560 microcontroller are used to output signals to the relays; and to provide power and ground to the thermocouple amplifier, water level sensors, photo resistors, and the liquid crystal display. Digital input pins will read the state (high/low) of the water level sensor circuits to control the operation of the solenoid valve, which allows the flow of seawater into the boiler. Additionally, analog input pins are used to read the state of a potentiometer and photoresistor as an analog value. The analog value for the photoresistor is read to determine the quality of sunlight, and to control the on/off operation of the system. A pulse width modulation (PWM) analog output pin sends a signal to the switching transistor to control the speed of the cooling fan for the external PWM motor driver. The duty cycle of the cooling fan is linearly related to the analog reading of the potentiometer, which ranges from 0 to

1024 [11]. Duty cycle is the proportion of 'on' time with respect to the regular interval. Analog values for the potentiometer, photo resistors, boiler temperature, as well as digital values for the float switch states can be viewed through the serial monitor on the Arduino Software using a PC connected via USB when data acquisition is necessary.

4.4 Sensors

4.4.1 Photoresistor

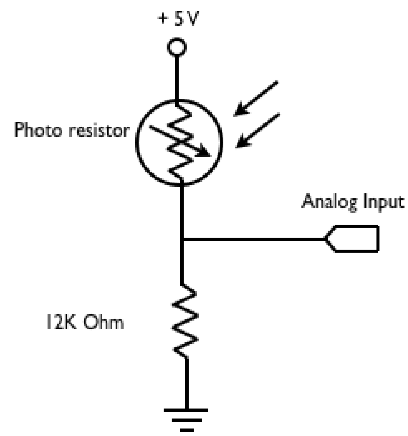

Figure 12: Photoresistor circuit

To sense the ambient light levels as an analog value, photoresistors are used as the top resistor in a voltage divider circuit. A photo resistor is a resistor that exhibits photoconductivity, where its resistance decreases with increasing light intensity. In this application, three cadmium sulfide photoresistors are connected in parallel as the top half of the voltage divider circuit, while a 12-kΩ resistor is placed on the bottom half, as shown in Figure 12. The photoresistors are angled so that the ambient light levels can be read consistently throughout the day with varying sun position. The light sensor is placed in the same housing as the single axis tracking system sensors on the upper, eastern end of the system. The Arduino Mega 2560 microcontroller reads the voltage at the midpoint of the voltage divider as an analog value using an analog input pin.

4.4.2 Float Switch

Two vertically mounted, high-temperature, float switches from Cynergy3 are used to determine the water level in the enclosed boiler. The float switches will be used to enable cyclic loading of seawater into the boiler to optimize the distillation process. Each float switch will be wired in series with a pull-down resistor as shown in Figure 13. The states of the float switches will be read by the microcontroller using a digital input pin to control the operation of the solenoid valve.

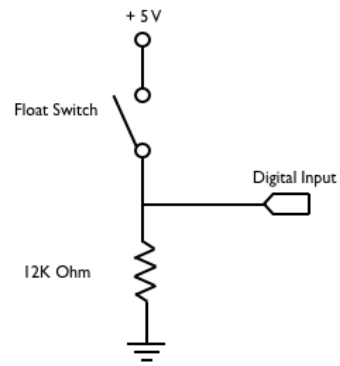

Figure 12: Float switch circuit

4.4.3 Thermocouple

A K-type thermocouple probe from Omega Engineering, Inc., will be used to measure the boiler temperature. Thermocouples use the thermoelectric effect to measure temperatures. Two dissimilar metals with known thermal expansion coefficients are soldered together at one end. Two wires extend from this point; and, together, they produce a voltage difference across them that is directly related to the temperature at the soldered end, known as the Seebeck voltage. Thermocouples can respond to changes in temperature very rapidly, but they are also sensitive to electromagnetic noise. This high sensitivity can compromise the quality of the readings if it is not taken into account. Therefore, it is important that the thermocouple wires are isolated from the relays, pumps, and motors throughout the system, which are all inductive loads that produce an electromotive force.

4.4.3a Signal Conditioning

The aforementioned Seebeck effect that takes place within a thermocouple only generates a signal in the millivolt range. This is too small of an analog voltage to be effectively digitized by most analog-to-digital converters (ADC). Therefore, amplification is required.

Thermocouples output a voltage that represents a temperature measurement in reference to the cold junction, at the end of the thermocouple wires. A cold junction compensator must be used to correlate the voltage across the two wires to the temperature at the hot junction, which is the signal that displays the most significant temperature. A cold junction compensator works by inserting a voltage that is related to ambient temperature, which is the same temperature as that of the end of the thermocouple wires. This compensator voltage cancels out the voltage contribution of the cold junction, thus leaving only the voltage from the hot junction of the thermocouple to be measured. A thermocouple will only have a zero volt output at 0°C, so, by canceling out the cold junction voltage, a temperature reading that is referenced to 0°C is obtained from the hot junction.

After the thermocouple is properly biased from the cold junction compensator, the hot junction voltage must be amplified and fed into an ADC to be digitized. An ideal amplifier for this process would have a low offset voltage, low drift, and low bias current to properly amplify the low thermocouple voltage. For a K-type thermocouple, a 12-bit amplifier configured with a negative feedback and a gain of 4095, would place the thermocouple voltage in the range of 0-5 V, as required by the Arduino Mega 2560 microcontroller [11]. This would meet the requirements of the ADC, while maintaining an acceptable degree of resolution. The Adafruit Industries thermocouple amplifier breakout board uses the MAX6675, a 12-bit ADC. This ADC allows readings from 0 to 1024°C with a resolution of 0.25°C. A capacitor is placed between power and ground to filter out any noise.

4.4.3b Processing

Once this signal has been digitized by the ADC, the signal is then processed by the microcontroller, where the digital representation of the analog voltage is calibrated. The output from the thermocouples will be between 0-5 V after the signal has been amplified. The ADC will output a number between 0 and 4096. This analog value will indicate the “step” relative to the 5 V scale. The step value must then be converted to a temperature reading by multiplying the step by a factor of (500/4095). For example, if the voltage read by the ADC were 1 V, the output from the ADC would be a byte correlating to the decimal value of 819. This is obtained by determining the number of steps to 1 V (4095/5 = 819 steps per volt), which must then be multiplied by (500/4095) to obtain the value of 100 [11]. At 10 mV/°C, 1 V indicates a temperature reading of 100°C.

4.5 Power Switching

To enable full control over the electrical components in the system, power switching is necessary. The Arduino Mega 2560 has the ability to output 40 mA at 5 V. This is not enough to power any of the system components, which range from 1.2-6.7 A at 12 V. Therefore, relays and switching transistors are used to control the components. Electromechanical relays are controlled using NPN switching transistors that control the vapor pump, solenoid valve, and the HTF pump.

An electromechanical relay is an electrically operated switch, which uses an electromagnet to operate a switching mechanism mechanically. Relays are typically used where it is necessary to control a higher powered circuit by use of a low power circuit while completely isolating the two. In this application, the control side of the relay is connected in series with an indicator light-emitting diode (LED) and general purpose NPN transistor. The purpose of the transistor is to act as a high-speed switch, and to provide enough current to power both the relay and the LED, since the microcontroller is not able to do so on its own. Since the relay is an inductive load, a flyback diode is used to eliminate sudden voltage spikes when the voltage is suddenly reduced or removed, as shown in Figure 14. These relays are rated at 12 V and 10 A, which is sufficient for our application of switching a 1.2-A vapor pump, 6.7-A HTF pump, and a 1.5-A solenoid valve at 12 V. Flyback diodes are also placed across the terminals of the solenoid valve, HTF pump, and the vapor pump to prevent voltage spikes and noise in the power lines.

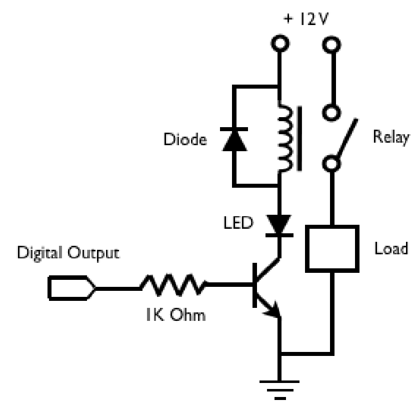

Figure 14: Transistor relay circuit

An NPN switching transistor can be used for controlling high power devices, such as motors, solenoids, or lamps. They have the ability to use low-voltage, low-current signal lines (such as a microcontroller I/O line) to control higher voltage, higher current devices. When the base of a transistor is subjected to PWM, the speed of the motor can be controlled as the transistor acts as a high-speed switch. The NPN switching transistor is used to control the speed of the external motor controller-cooling fan, where the PWM signal is varied by adjusting the potentiometer.

The control side of the relays and transistor require only 5 V and can easily be controlled by the digital or analog I/O pins from the Arduino Mega 2560 microcontroller, with the use of a general purpose NPN transistor to provide a stronger current draw. The relays and transistor also have indicator LEDs to show when each component is in operation. Each component is protected by a fuse, which varies in size, depending on the component. A fuse is a low resistance resistor that acts as a sacrificial device to provide protection to components or circuitry from large current spikes. The vapor pump and solenoid valve are protected by 2.5-A fuses; the Arduino micro controller is protected by a 1-A fuse; and the HTF pump is protected by a 10-A fuse. Electrical switches allow the user to turn on/off power to each component, while a second set of switches allow the user to either use the control system, or to manually override the control system and force the component on.

4.5.1 Motor Driver

A motor speed controller from Cana Kit is used to control the speed of the DC HTF using PWM. The controller has two modes of operation: fixed or variable frequency. The fixed frequency mode of operation runs the controller at 100 Hz. In the variable frequency mode of operation, the frequency is adjustable from 244 Hz to 3.125 KHz. The duty cycle is fully adjustable from 0% to 100% in both modes. This will enable full control of HTF flow rate by adjusting the duty cycle and frequency of the circulation pump. The cooling fan will be used to dissipate heat from the motor driver, keeping it within operational temperatures. The motor driver operation is controlled by the electromechanical relays driven by the Arduino MEGA 2560 microcontroller through a switching transistor.

4.5.2 Solar Tracking Controller

A solar tracking controller from Spelling Business Enterprises is used to drive the geared motor, which controls the single axis tracking system. The solar tracking controller uses a differential light sensor with four photoresistors to sense the position of the sun. This controller has enough hysteresis built-in to prevent oscillation of the system. However, a potentiometer can be used to adjust the sensitivity of each photoresistor. Mercury tilt switches set the limits of operation for the solar tracking system to ensure that the troughs do not interfere with the structure.

4.6 Software Implementation

The instrumentation as well as the control system is integrated into an Arduino MEGA 2560 microcontroller which uses Arduino software. The open-source Arduino software runs on

Windows, Mac OS X, and Linux. The software is written in Java and is based on Processing, avr-gcc, and other open source software.

4.7 Choice of Controller

The Arduino Mega 2560 microcontroller was chosen because of its ease of use and the team's familiarity with its development environment. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 universal asynchronous receiver/transmitters (UART) that are hardware serial ports, a 16-MHz crystal oscillator, a USB connection, a power jack, an in-circuit serial program (ICSP) header, a reset button, 4 KB of electrically erasable programmable read-only memory (EEPROM), 8 KB of static random-access memory (SRAM), and 256 KB of flash memory.

4.8 Control System Logic

The system controls the following elements: HTF Pump, Vapor Pump, Solenoid Valve as shown in Figure 15. The control algorithm works in the following manner:

1 The system starts by reading the ambient light level as an analog value. If the ambient light reading is less than 500, all components are off. If the ambient light reading is greater than 500, the HTF pump is turned on.

2 The boiler temperature is read by the thermocouple and the vapor pump remains off until the boiler temperature is greater than 100°C.

3 If the state of both float switches are read as 'low,' the solenoid valve opens until the state of both float switches are read as 'high.'

4 Process starts again.

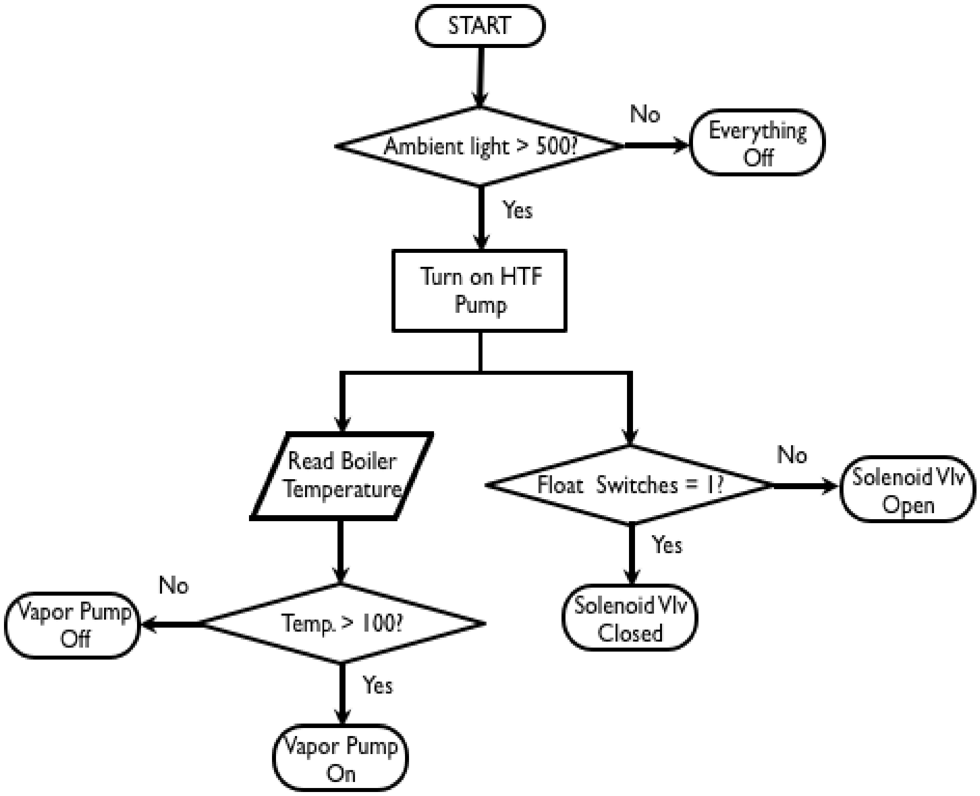

Figure 13: Control system block diagram

Section 5: System Integration, Tests, and Results

5.1 Integration, Tests, and Results

After completing the construction of the system, preliminary boiler temperature tests were conducted to verify that heat transfer was efficiently occurring through the solar troughs and through the heat exchanger inside the boiler. Simultaneously, minor leaks were located and re-soldered throughout the system's piping to prevent any heat loss and piping failures. Figure 16 shows a few representative trials of several tests that were run over several days while varying the mass flow rate of the HTF between 0.05 kg/s and 0.125 kg/s. For a complete representation of preliminary data collected, refer to Appendix O. Through these preliminary tests, it was concluded that the solar troughs were not collecting enough energy to reach the desired boiler temperature of 100°C; therefore, immediate design modifications were necessary.

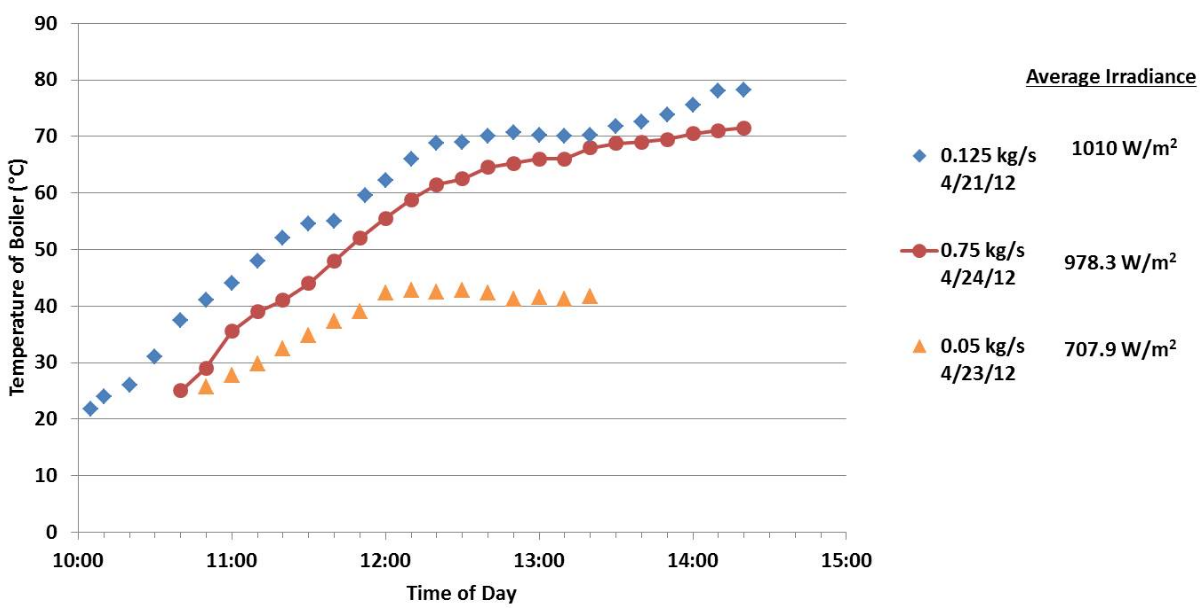

Figure 14: Initial testing of boiler temperature over time

The solar parabolic troughs (herein named "troughs") were initially assembled in relation to the trough's fixed collector pipe in such a way that the pipe would like along the trough's focal line. This focal line was based on the theoretical focal point of the trough's parabolic equation. However, there were local deformities along the trough's face due to the team's construction. The consistency of the curvature of the trough was examined by aiming a laser pointer normal to the trough's surface, while moving the pointer from one edge to the other edge. As this was done, the location where the laser light reflected was noted, as illustrated in Figure 17. This experiment showed that approximately 13 cm from each edge of both troughs were not focused directly toward the collector pipe. To address the issue of lost focused light, the distance between the collector pipe and the trough was experimentally adjusted to match the actual focal length of the parabolic troughs.

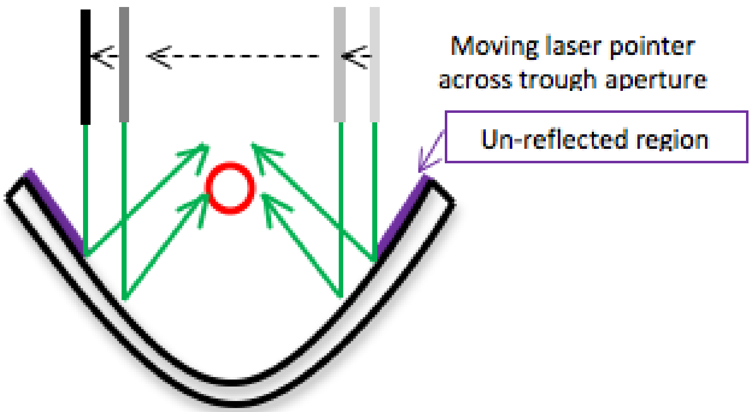

Figure 15: Laser pointer test

To adjust the space between the collector pipe and the trough, notches were drilled into a prototype trough hanger at 1.3 cm increments, as shown in Figure 18. In doing so, the troughs were iteratively tested at each adjusted increment; the effectiveness of each adjustment was verified using the laser pointer test. It was discovered that lowering the trough 1.3 cm focused more sunlight on the fixed collector pipe. The 13 cm loss from each edge diminished to a length of about 3.8 cm on each edge. In addition, the calculated area of lost reflective surface decreased by a factor of about three.

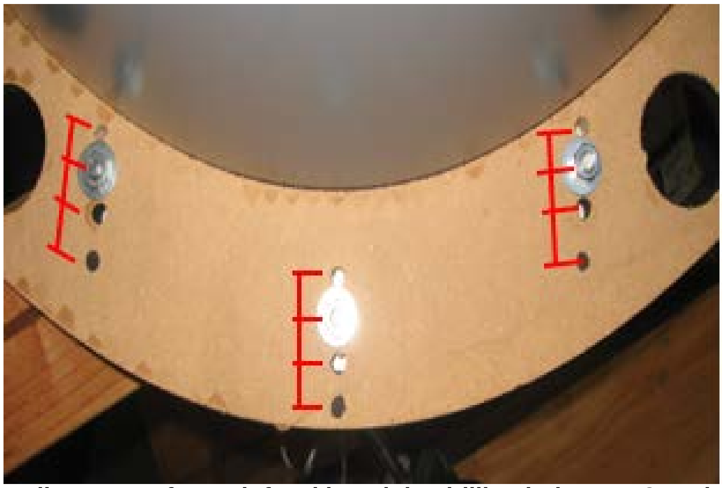

Figure 16: Adjustment of trough focal length by drilling holes at 1.3 cm increments

New temperature tests were conducted to compare the boiler temperatures of the original trough design to the lowered trough design (Figure 19). This graph is a representative sampling of the all the data collected (more comprehensive data can be viewed in Appendix O. The boiler temperature peaked at about 80°C during these tests, compared to peak temperature of about 70°C during previous tests. Continued experimentation and further improvements were made on the newly adjusted troughs due to their overall better performance. Unfortunately, even after adjusting the hangers to match the focal length, the boiler still did not reach the target temperature of 100°C. Other ways to help improve the overall system were researched.

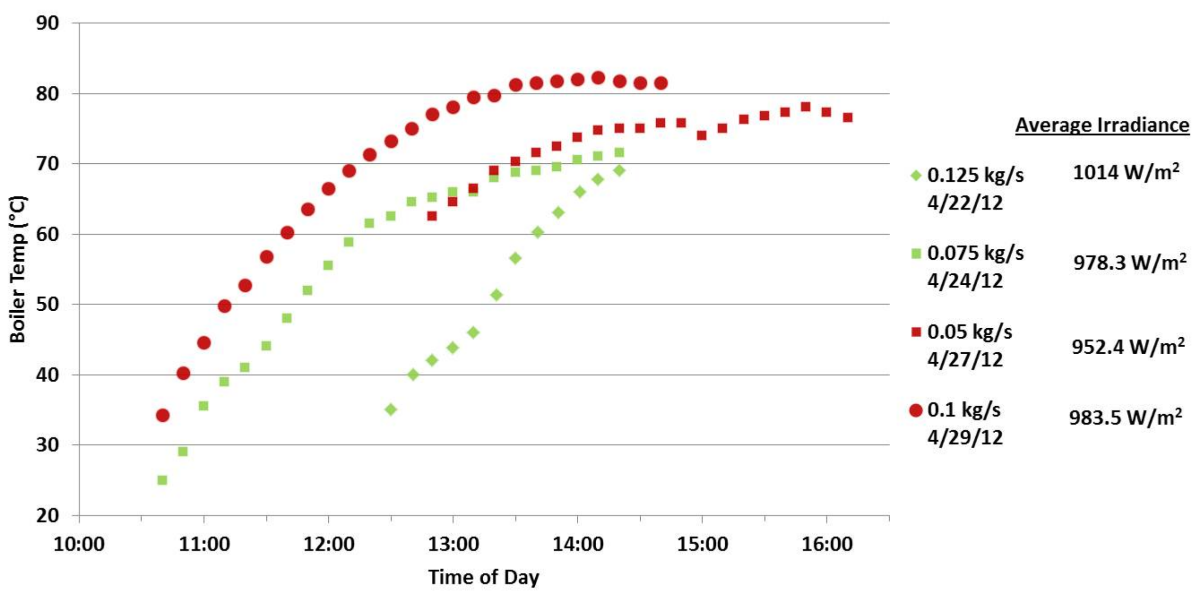

Figure 17: Boiler temperature comparison between original and adjusted troughs

One modification pursued was the addition of a convection/radiation heat loss envelope. This envelope was made out of a polycarbonate tube that encased the entire length of the copper collector pipe. It mimicked that of an evacuated tube collector without the vacuum pressure. It was intended to keep the temperature right around the pipe hotter than the cooler ambient surrounding air temperature. It also acted as a shield, preventing convective heat loss from any wind that might have picked up heat radiating off the surface of the copper piping, as seen in Figure 20. However, there was a tradeoff: the polycarbonate material has an 86% light transmissivity rating. This means that the transparent polycarbonate material blocks a fraction of the light that the pipe could absorb. So, although the envelope's function is to minimize heat loss, the addition of the envelope also negatively affects the amount of energy input to the system. Further tests were needed to analyze the effect on the overall system.

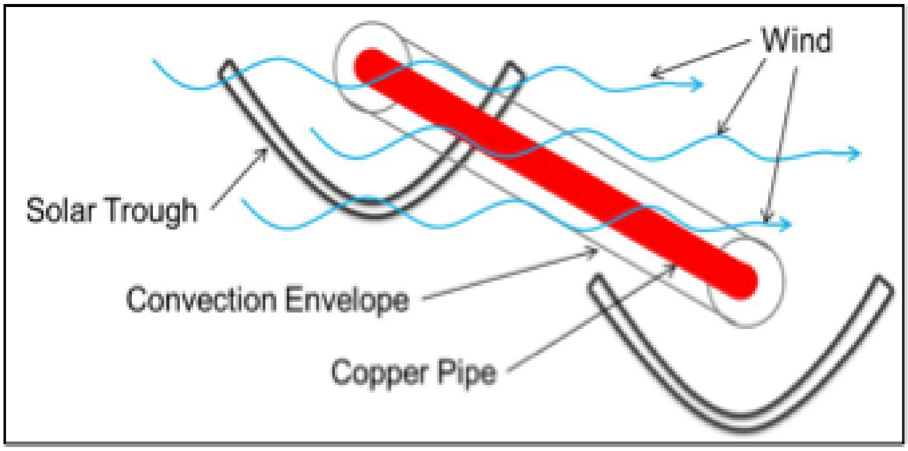

Figure 18: Effect of the convection/radiation heat loss envelope

Figure 21 shows the comparison of the boiler temperature of the system with and without the convection/radiation heat loss envelope. From this data, along with all the data collected during this experiment (see Appendix O), the comparisons remained inconclusive due to the very similar peak boiler temperature points. Instead of focusing on the temperature of the boiler, the efficiencies of both designs (with and without the convection/radiation cover) were compared and evaluated. The trough efficiency is calculated using:

$$\eta = \frac{Q_{trough}}{Q_{irradiance} A_{aperture,trough}} \quad (9)$$

where $Q_{irradiance}$ is the irradiance from the sun normal to the surface of the trough, A is the aperture area of both troughs, and Q_{trough} is the energy absorbed by the HTF flowing through the troughs defined by:

$$Q_{trough} = \dot{m} C_p \Delta T \quad (10)$$

where $\dot{m}$ is the mass flow rate, C_p is the specific heat of the HTF and ΔT is the change in temperature between the inlet and outlet points of the trough. Using the efficiency allows for the analysis of the troughs while accounting for multiple and various changing parameters.

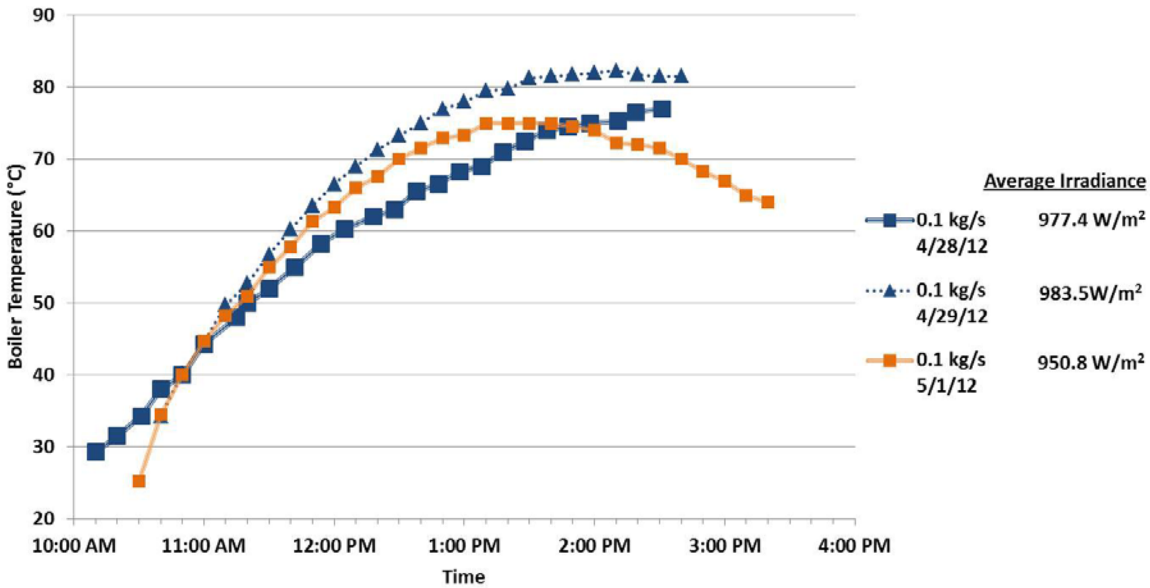

Figure 19: Boiler temperature comparison with and without convection/radiation heat loss envelope

Table 4 depicts a table comparing the efficiencies of the tests with and without the envelope. The average efficiency of each day was calculated and the averages of those efficiencies were taken. It was concluded that because the efficiencies of the tests with the envelope were generally higher, the system would continue to be analyzed with the addition of the convection/radiation heat loss envelope.

Table 4: Efficiency comparison with and without convection/radiation heat loss envelope

Trial		Average Efficiency(%)		Average Irradiance (W/m^2)
Without Convective Envelope	4/27/12	34.5	42.8	952.4
	4/28/12	37.8		977.4
	4/29/12	56.0		983.5
With Convective Envelope	4/30/12	44.0	50.7	864.6
	5/1/12	44.4		950.8
	5/2/12	63.8		875.4

It was during this time of the system's design and analysis that the integration of the two separate EES models (trough analysis and boiler/HEX analysis) revealed a new flow rate that would yield better temperature results. The new flow rate of 0.015 kg/s with the convective envelope was tested and compared to the results of the system with the envelope at other various flow rates. Figure 22 shows a definitive difference between the old flow rate of 0.1 kg/s and the new flow rate of 0.015 kg/s. The system reached an overall higher boiler temperature with an all-time high peak reading of 95.25°C. This test confirmed the target EES model flow rate.

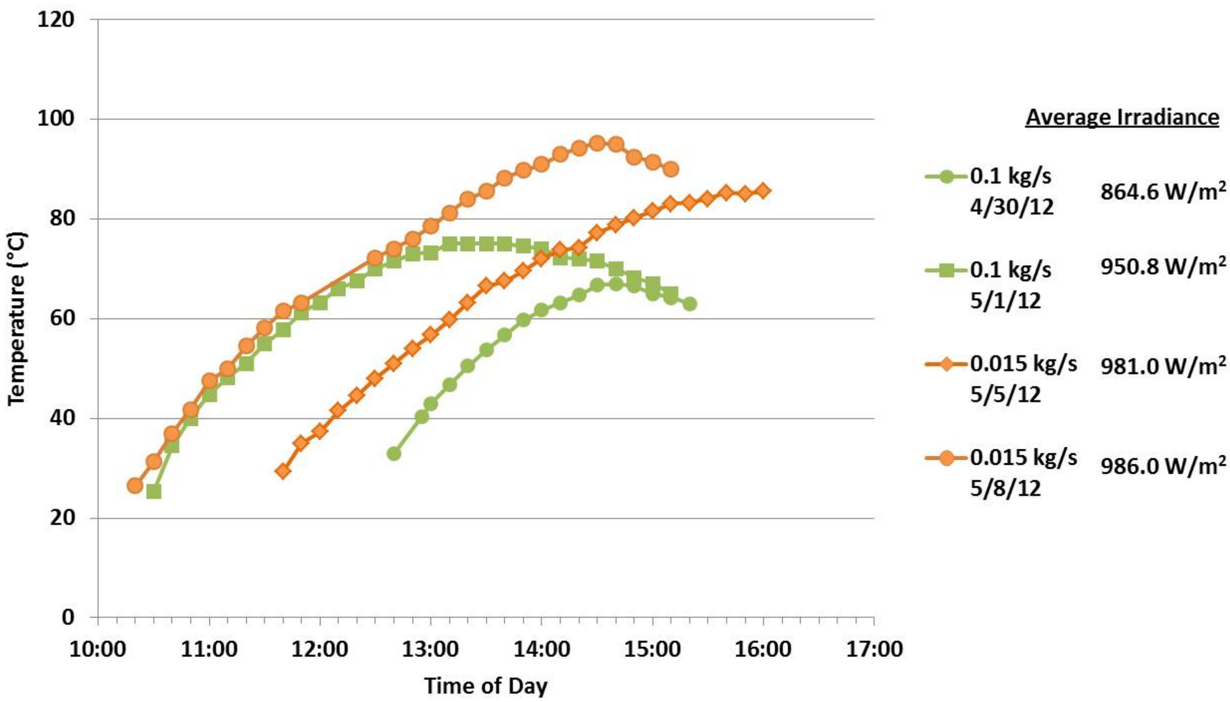

Figure 20: Boiler temperature comparison between flow rates

Section 6: Business Plan

6.1 Company Goals and Objectives

Future water demand is predicted to increase while current resources are continuously depleting. The team has, therefore, designed a standalone, off-the-grid water purification system that provides an economically sustainable model for producing clean drinking water; this is achieved using solar parabolic troughs for the distillation process. This system falls between reverse osmosis and solar stills in terms of price and performance. The team specializes in manufacturing and developing the water purification system, which will be sold to non-profit organizations that help needy coastal communities, as well as to agencies aiding in disaster relief.

6.2 Potential Market

Clean water is not an unlimited resource and it is something most developed nations take for granted. Only 3% of the World's water is actually fresh water, leaving the rest as undrinkable ocean water. Fresh water is even scarcer in developing countries and areas destroyed after natural disasters, such as the Haiti earthquake. Therefore, our system was designed with the intent of helping developing coastal communities that have a limited supply of fresh water. The targeted communities would be in developing countries, on the coast, and in sunny regions. This would be ideal because the communities could use the ocean water and sun to power the system and produce clean water. We would, therefore, sell our system to non-profit organizations that could implement the system in developing coastal communities and for disaster relief.

Due to the fact that the Solar-Powered Water Purification System is scalable, the system can produce more water with additional solar troughs. The system could, therefore, be marketed in developed countries that have a much higher demand for clean water. This would include residential areas, large-scale desalination plants, military locations, and "green" businesses that want to implement our technology. These potential buyers should be in sunny areas to yield maximum efficiency of system.

6.3 Personnel

The engineering behind the Solar-Powered Water Purification System would be done in the Silicon Valley of California. Silicon Valley is a great place to develop the system because it is a place where sustainable energy is quickly progressing and where there is a high number of college graduates who are seeking jobs in the sustainable industry. In addition to hiring engineers, business majors would be hired to help aid the company. Business majors will manage company finances, while engineers will focus on designing the system, as well as improving manufacturing processes. The company would also hire manufacturing personnel to assemble the system. By manufacturing in-house, the company will support American jobs, as well as cut down on importing shipping costs.

6.4 Advertising and Sales Strategies

Advertising has become much easier due to the development of technology and easier access to helpful tools. A detailed website would be created to make all information about the system and technology readily available for the general public. In addition, Google, social networking, and magazine advertising tools would be utilized for additional awareness. As the team further develops, a recently graduated marketing major would be hired to help assist the team with the marketing strategy. These marketing ideas would help spark more awareness of the company and technology in the United States.

6.5 Distribution

The Solar-Powered Water Purification System was designed to fit in a standard-sized shipping container. It will also be further designed to be more robust and durable for the shipping journey to its final destination. Sales will primarily be direct, with worldwide shipping done through companies such as Matson, and Horizon Lines, Inc.

6.6 Manufacturing Plans

The team would manufacture the Solar-Powered Water Purification System in-house. A total of 75 units would be made the first year with a 30% unit increase each year. The parts will be manufactured, unless they were readily available from a vendor and/or made more financial sense. As the time goes on and clientele increases, more employees would be hired to help with the manufacturing and assembly workload. Since the area of the system is about the size of a king size bed, a suitable working area would be needed to store parts and manufacture the system. A small warehouse would be necessary and will allow for the system to be produced in a timely manner.

6.7 Product Cost and Price

The Solar-Powered Water Purification System would have a manufacturing cost of about $3,000 per unit with a retail value of $5,000 per unit. This would give a $2,000 profit per unit and an estimated growth rate of 30% annually. Some of the startup expenses would include facilities and equipment, advertising, website, legal and professional salaries, and contract services.

6.8 Service and Warranty

The team's Solar-Powered Water Purification System requires minimal service due to its strategic design. The boiler will need to be cleaned approximately once a month to remove excess brine and salt from the bottom of the tank. This can be done by simply spraying or flushing out the boiler with cleaner water and draining it through the exit at the bottom. In order to reach the maximum efficiency, it is essential that the solar trough mirrors are always clean. If dirty, they can be cleaned with a cloth material that wipes off dirt and grime, and increases reflectivity.

The maximum life span of the system is 10 years. At this time, the pumps and HTF will need to be replaced in order to maintain their efficiency. Overall, the system is designed to be completely stand-alone and will operate when the "on" switch is turned on. It will have no other maintenance requirements besides the cleaning. Therefore, the system will run for 10 years and will require very little education to keep it operating.

6.9 Financial Plan and Return on Investment

As a startup company, the team would request $100,000 from investors for funding. The pre-money value and post-money value would be $750,000 and $850,000, respectively. A $100,00 investment would give a 12% investor share and a return on investment, in 5 years, of about 237% (refer to Figure 23). As an exit plan, the team would stay as a private company and would further develop the product and business. Not only would investors receive a great return on investment, but they would also be helping solve the World's demand for clean water in a sustainable way.

selling at $5000	2012	2013	2014	2015	2016
units	75	98	127	165	214
salaries	-100,000	-130000	-160000	-190000	-220000
facilities	-50,000	-50000	-50000	-50000	-50000
manufacturing cost	-225,000	-294000	-381000	-495000	-642000
sales	375000	490000	635000	825000	1070000
Revenue	**0**	**16000**	**44000**	**90000**	**158000**

Figure 21: Return on investment for the Solar-Powered Water Purification System

Section 7: Engineering Standards and Realistic Constraints

7.1 Societal Influence

The Solar-Powered Water Purification System has widespread implications on the wellbeing of society through the vast improvement of public health in various portions of the world. The system utilizes a comprehensive distillation process, by which the dirtied water is shed of both its organic and inorganic contaminants. The World Health Organization (WHO) estimates that 4.1% of the total global burden of disease can be attributed to waterborne diseases, leading to an average of 1.8 million deaths per year [7]. 88% of these deaths can be directly attributed to waterborne diseases, due specifically to poor water sanitation and hygiene practices.

The most prominent illness comes in the form of diarrheal disease, which accelerates dehydration in areas that already lack an adequate supply of clean water. This form of illness is the result of protozoal infections such as: Amoebiasis, Cryptosporidiosis, and Giardiasis, which have a strong presence in untreated water. Similarly, a number of familiar types of bacterial infection like, E. coli, Dysentery, Leptospirosis, and Typhoid fever, are all attributed to the consumption of unsafe water. A number of more serious illnesses, such as the parasitic Guinea Worm, Hepatitis A, and Polio, can be contracted from untreated water and very commonly lead to death [8]. The Solar-Powered Water Purification System deals with these organic contaminants through the use of high-temperature water pasteurization. The goal of pasteurization is different from sterilization. Instead of focusing on the complete degradation of all contaminants, pasteurization aims to reduce the number of viable contaminants to a level where they are unable to cause sickness. In the milk industry, it is common practice to heat milk up to 71°C for a duration of 15 seconds, resulting in a 99.999% reduction in harmful micro-organisms, with an overall effectiveness of around 90% in the elimination of harmful bacteria within milk [9]. The Solar-Powered Water Purification System progressively heats unpurified water up throughout the day to temperatures in excess of 100°C, while the water itself is sustained at temperatures above 71°C for anywhere from 45-90 minutes. This vastly exceeds the accepted pasteurization procedures carried out in the milk industry. However, just the removal of microbial infection is not enough to adequately purify water.

Untreated water is also subject to a number of inorganic contaminants, which can cause a wide variety of unwanted illnesses, making the water undrinkable. These contaminants include: salt, silt, lead, nitrate, and volatile organic compounds [10]. The distillation process serves to separate any inorganic compounds with a higher boiling point than dihydrogen oxide exclusively through its evaporation and recollection. The once dissolved heavy metals and nitrates are left behind in solid form, where they can be safely disposed of. In addition, highly volatile and dangerous organic compounds, including a number of pesticides and herbicides, are quickly vaporized; and, thus, removed from the water in the early stages of the distillation process.

The system is aimed at providing an average of 30 L of water per day resulting in a cost of \$0.046 per liter of water. However, the system is not limited to a 30 L production and can be scaled to accommodate any communal water requirement. Similarly, the cost of producing clean water is 50% lower than the average \$2.00 fee for an 18.9 L jug of chlorine treated water. The low price and high level of self-sustainability create an attractive option for communities in need of a medium to large scale method of purifying water, and ultimately makes the acquisition of clean water more accessible to everyone. By providing a self-sufficient, comprehensive, and scalable solution to the world's shortage of clean water, the quality of life for many people around the world can immediately be improved with only a minor financial investment.

7.2 Environmental Impact

Water distillation requires a large quantity of energy to take place. This energy can be supplied from a variety of sources, such as electricity and fossil fuels. However, burning fossil fuels result in large quantities of carbon dioxide emissions to the atmosphere. To minimize the environmental impact of the water distillation system, solar energy, a renewable clean source of energy, was used. Solar parabolic troughs are used to collect heat from the sun by reflecting its rays onto a central focal length, and transferring its heat to a non-toxic HTF. PV panels are used to produce the electricity necessary for operation of the system's electrical components.

The total power consumption of the system is 130 W when all of the components are in use. The microcontroller, vapor pump, solar tracking motor, solenoid valve, fan, and HTF pump consume 1, 15, 15, 18, 1, and 80 W, respectively. By implementing a control system, these electrical components can be turned on and off as needed to minimize the power consumption and size of the PV panel. A 120-W monocrystalline PV panel is used to power the entire system, making it completely off-grid. A single axis tracking system is used to minimize the cosine loss that is typical of static panels, thereby increasing its efficiency.

In addition to having no carbon dioxide emissions, the Solar-Powered Water Purification System produces very little noise. The loudest component in the system is the HTF pump. By controlling its speed using PWM and variable frequency, both the duty cycle and noise are lowered.

By producing a system that uses only the energy captured from the sun to power its components and to distill water, carbon dioxide emissions will be minimized. In addition, no power lines will be needed to operate the low-noise system.

7.3 Sustainability Impact

The Solar-Powered Water Purification System is designed with sustainability as one of its main design requirements. The operation of the system has been designed to be based solely on energy provided from the sun; thus, the entire heating process of the water, circulation of the vapor and HTF of the system, and the positional tracking of the solar collectors is done without the need for external electric or fuel sources. This results in the system having zero emissions, and relatively minor amounts of by-products. These by-products would generally be limited to salt cakes that form in the boiler after extended periods of distillation. However, these salt cakes could potentially be used or sold as salt licks for livestock, or even used as a means for nutrition and food preservation.

7.4 Economic Impact

When designing the Solar-Powered Water Purification System, the team aimed to sell the product to non-profit organizations (for use in developing nations near coastal regions) and to disaster relief agencies. Due to the limited funds of these groups, the system had to be retailed at a competitive price. Solar parabolic troughs were employed over the previous Mazdon solar collectors due to two main reasons. First, one Mazdon solar collector with 20 tubes costs approximately $2,650. On the other hand, each solar parabolic trough costs about $300. Therefore, more energy can be achieved for a lower cost by employing solar parabolic troughs. The second reason solar collectors are more desirous is that they are able to achieve temperatures above 100°C; therefore, the pressure within the boiler does not have to be lowered (as is the case with the Mazdon solar collectors).

Overall, the cost to produce the system is $3,000, and it would be retailed at $5,000. This price is attractive for agencies with limited funding. Additionally, more solar collectors can easily be added to yield higher water production levels. Since the cost of each collector is only $300, the productivity can be scaled easily and for a small additional cost. The Solar-Powered Water Purification System will require the buyer to pay an initial upfront cost; however, the cost will more than pay for itself over the system's lifespan. In addition, the system is competitive with current products on the market, with the advantage that it does not require maintenance like the other products.

With regards to the product's financial development, refer to the business plan in Section 6.

7.5 Health and Safety Impact

The Solar-Powered Water Purification System poses many safety and health risks since it reaches very high temperatures and produces its own electricity. Many of the surfaces on the system are at temperatures that sometimes exceed 100°C. These surfaces include the HTF circulation piping and the boiler. To improve system efficiency, these hot surfaces are insulated to prevent heat loss. The insulation doubles as a safety buffer, preventing these surfaces from being touched by its users. Similarly, the envelopes placed over each of the parabolic trough collector tubes insulate the system while preventing users from touching its surface.

The system uses a 12 V, 120-W PV panel to produce electricity for component operation. To prevent overcharging of the battery, a solar charge controller is used. Severely overcharged batteries can explode, leaving its surroundings covered in battery acid. The charge controller shuts off current flow to the battery when its maximum capacity has been reached. To protect users from potential electrical shock, the system must be properly grounded, using the grounding rod. The electrical components are all housed in insulated, weatherproof boxes, and the wires are run through conduit to minimize exposed wire.

In addition, proper selection of materials and components will prevent electrical components from overheating and causing potential burn hazards.

Section 8: Conclusion

8.1 Summary

During the spring quarter of 2011, six peers decided to follow up on 2010-2011's Team Clean Water's Solar Water Purification System. Thus, the Solar-Powered Water Purification System team was formed for the 2011-2012 Senior Design Project. The team was given the task to improve the previous year's system; but, after much discussion the team decided to create a completely new design. Scrapping only a few components from the previous year's project, a completely new Solar-Powered Water Purification System was designed and built during the 2011-2012 school year.

The Solar-Powered Water Purification System was designed with the parameters of being sustainable/off-grid, portable, cost effective, easy to use, and scalable. These parameters were achieved by using solar troughs, which are cost effective, scalable, and can reach boiling temperatures for the distillation process, which is a sustainable and cost effective way to produce clean water. The solar troughs were built using George Plhak's "How to Build a Tracking Parabolic Solar Collector" instruction manual. A control system was also used and powered by a PV panel to make the system off-the-grid and easy to use.

Appendices

Appendix A: Bibliography

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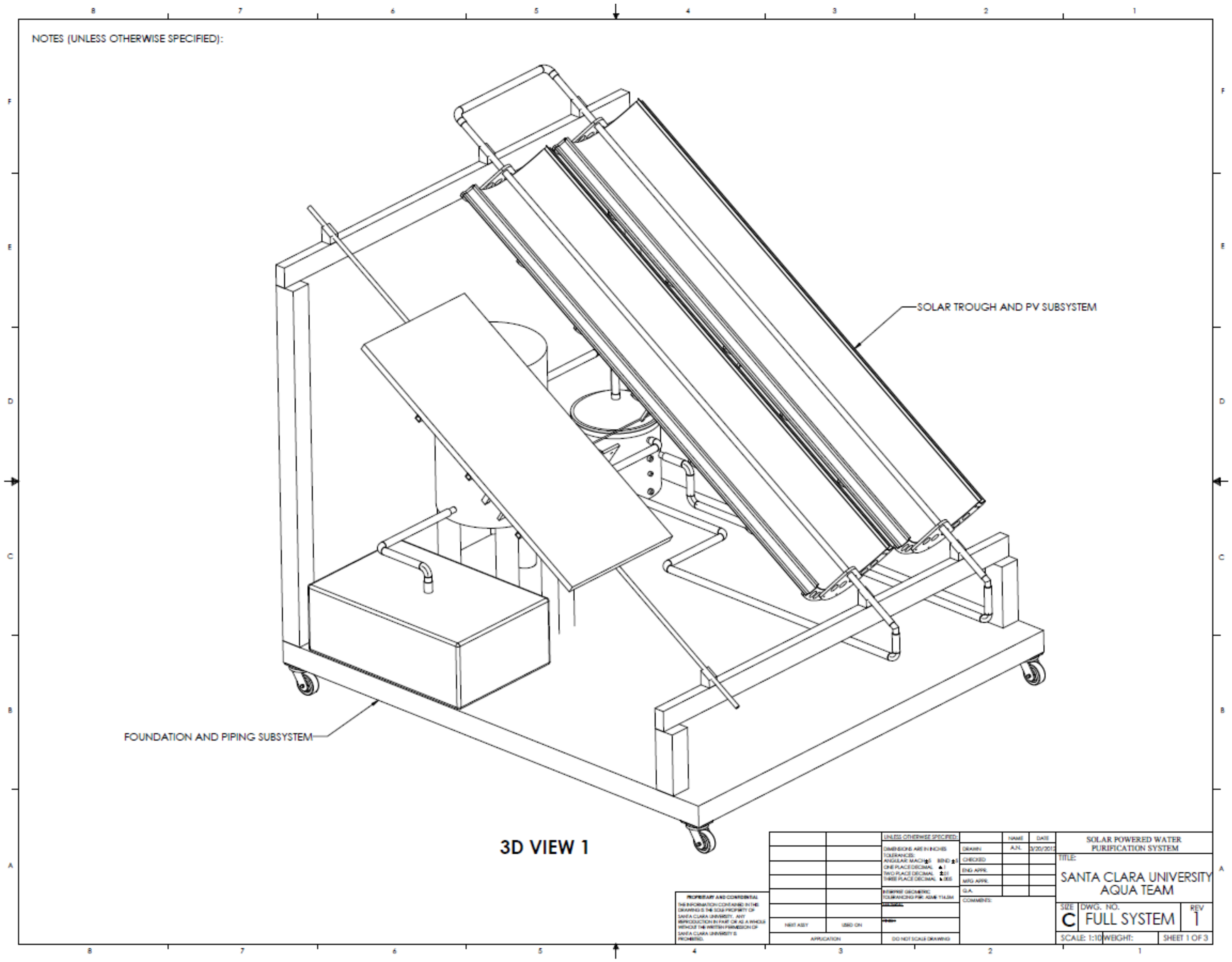
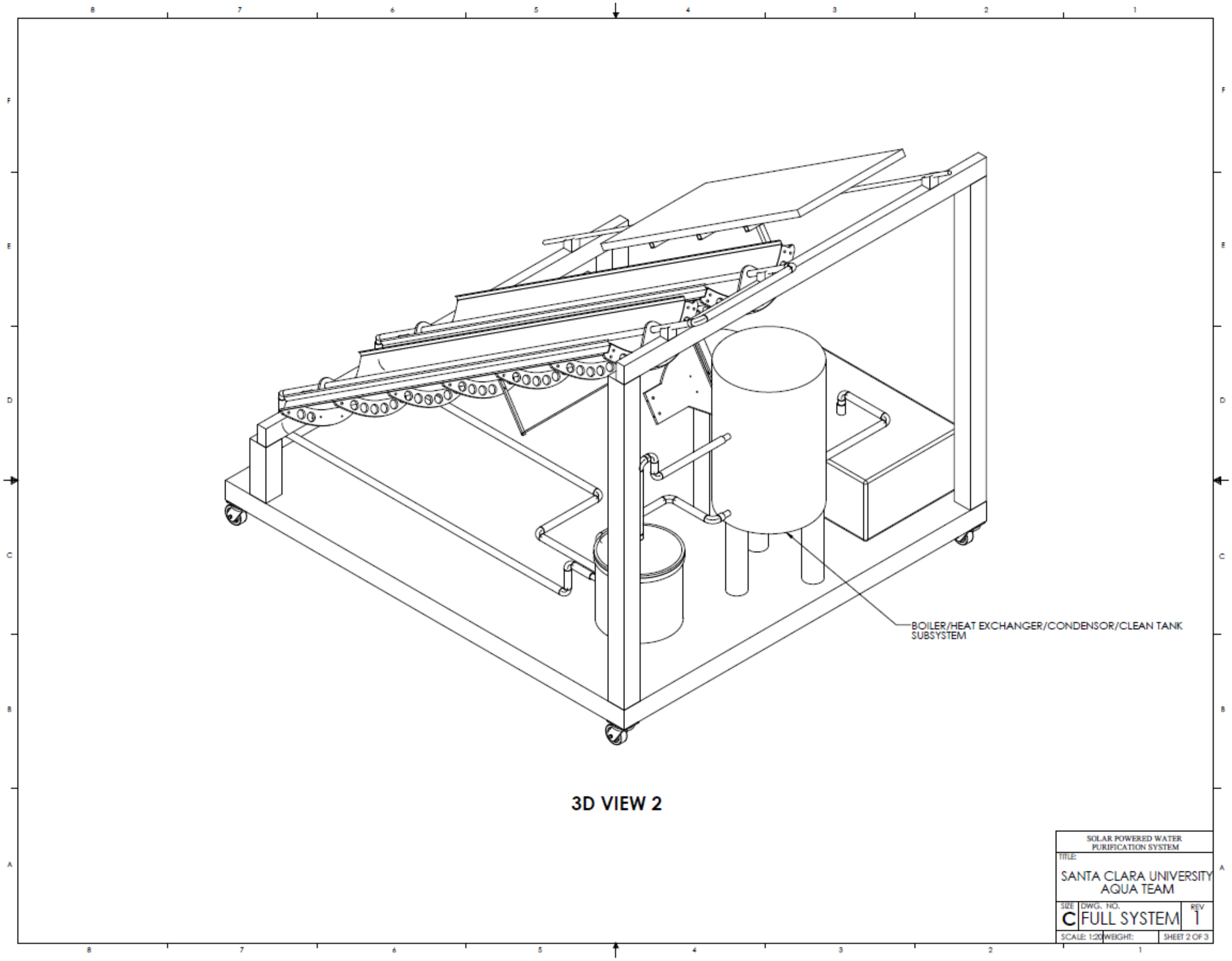
Appendix B: Assembly Drawings

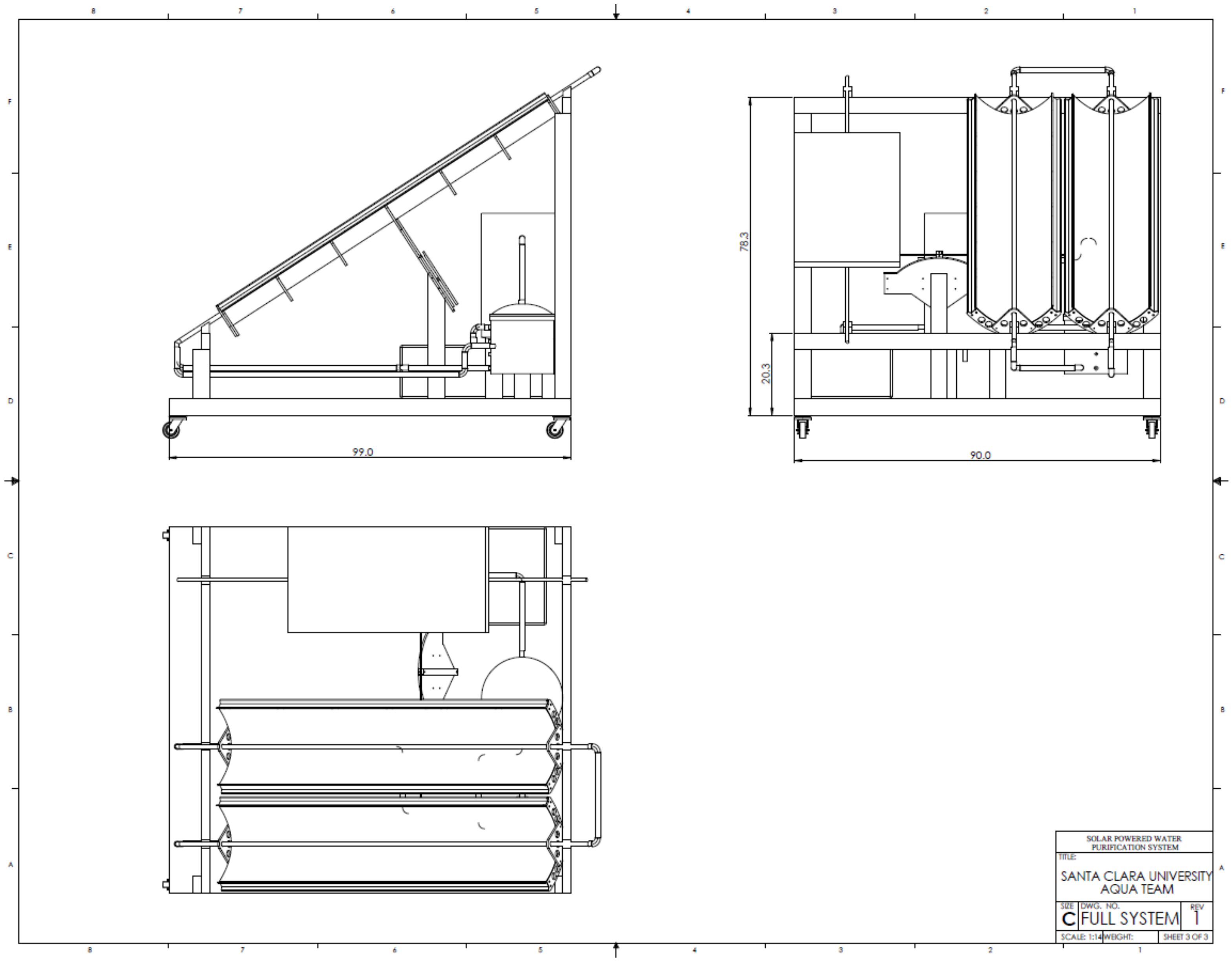
B.1 Parts List

Project	**Team Aqua - Solar Water Purification System**													
Version 1	**Monday, January 23, 2012**													
Subsystem	Component Description	Part #	# of Items	B/M/O	Vendor	Cost/Part	Responsible Person	Man Hours	Des	Proc	Build (ea)	Assm	Order or Start Date	Receive or Finish Date
Solar	Ribs	S001	7	M	Lowe's	$ 0.69	Chris, Reece	6.7	3	0.2	1.5	2	1/18/2012	1/27/2012
	Hangers	S002	2	M	Lowe's	$ 0.62	Andrew	6.7	3	0.2	1.5	2	1/18/2012	1/27/2012
	Side Channel	S003	2	B	Clark Dietrich	$ 5.00	Erin	3	1	1	0	1	1/18/2012	2/1/2012
	Reflector Sheet	S004	1	B	Lowe's	$ 8.00	Erin	4	1	1	0	2	1/18/2012	2/1/2012
	Foam Strips	S005	2	B	Lowe's	$ 2.42	Chris	0.6	0.2	0.2	0	0.2	1/18/2012	1/27/2012
	Copper Collector Tube	S006	1	B	Lowe's	$ 42.64	Erin	2.2	0.2	1	0	1	1/18/2012	2/1/2012
	Heat Shrink	S007	1	B	Tool Fetch	$ 54.00	Erin	1.2	0.5	0.2	0	0.5	1/18/2012	2/1/2012
	Cross Dowell	S008	28	B	Lee Valley	$ 0.24	Erin	0.9	0.5	0.2	0	0.2	1/18/2012	2/1/2012
	Bolts	S009	34	B	Lowe's	$ 0.50	Reece	0.6	0.2	0.2	0	0.2	1/18/2012	1/27/2012
	Washers	S010	12	B	Lowe's	$ 0.10	Chris	0.6	0.2	0.2	0	0.2	1/18/2012	1/27/2012
	Hex Nuts	S011	6	B	Lowe's	$ 0.25	Reece	0.6	0.2	0.2	0	0.2	1/18/2012	1/27/2012
	Copper Pipe Adaptor	S012	2	B	Lowe's	$ 10.30	Chris	0.9	0.5	0.2	0	0.2	1/18/2012	2/1/2012
	Copper Long End Elbow	S013	2	B	Sears	$ 4.00	Chris	0.9	0.5	0.2	0	0.2	1/18/2012	2/1/2012
	PV Panel	S014	1	B	Suntech	$ 294.00	Reece	5	2	2	0	1	2/14/2012	3/7/2012
	Solar Charge Controller	S015	1	B	Suntech	$ 80.00	Reece	2	1	0.5	0	0.5	2/14/2012	3/7/2012
	Motor Drive Assembly	S016	1	M	Lowe's	$ 0.69	Andrew	2						
	Subsystem Totals					$ 503.45		35.9						
Pumps	Vapor Pump	P001	1	B	Greylor	$ 80.00	Alex	5.2	4	1	0	0.2	1/27/2012	2/29/2012
	Subsystem Totals					$ 80.00		5.2						
Clean Water	Clean Water Tank	C001	1	B	Plastic Mart	$ 100.00	Erin	2.5	1	0.5	0	1	1/20/2012	2/29/2012
	Subsystem Totals					$ 100.00		2.5						
Foundation	Trough/PV Panel Frame	F001	1	M	Lowe's	$ 9.92	Andrew	6.5	3	1	1.5	1	2/1/2012	2/29/2012
	System Platform	F002	1	M	Lowe's	$ 89.94	Chris	5	1.5	1	1.5	1	2/1/2012	2/29/2012
	Subsystem Totals					$ 99.86		11.5						
Boiler	Body - HDPE Tank	B001	1	B	JD Skiles	$ 200.00	Andrew	9	2	1	5	1	2/6/2012	2/20/2012
	Float Valve	B002	1	B	McMaster-Carr	$ 30.00	Alex	2	0	1	0	1	2/13/2012	2/15/2012
	Heat Exchanger	B003	1	M	Home Depot	$ 80.00	Alina	18	5	1	10	2	2/6/2012	2/25/2012
	Bulkhead Connector	B004	2	B	JD Skiles	$ 11.00	Alina	2	1	1	0	0	2/13/2012	2/15/2012
	Condensor	B005	1	M	Home Depot	$ 100.00	Andrew	20						
	Subsystem Totals					$ 421.00		51						
Project Totals						**$1,204.31**		**106.1**	**30.5**	**14.5**	**21**	**18.1**		

B.2 Solar-Powered Water Purification System Assembly

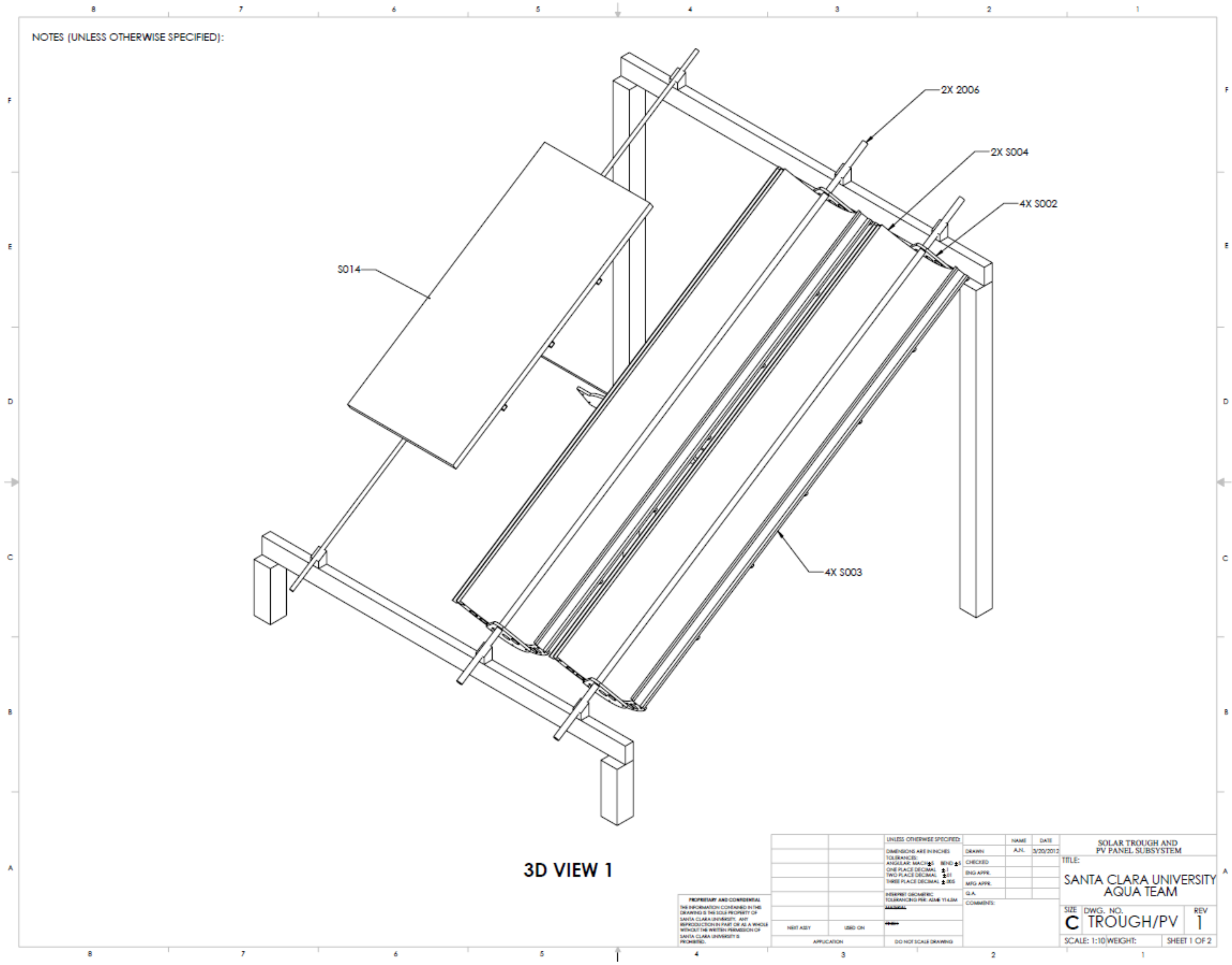


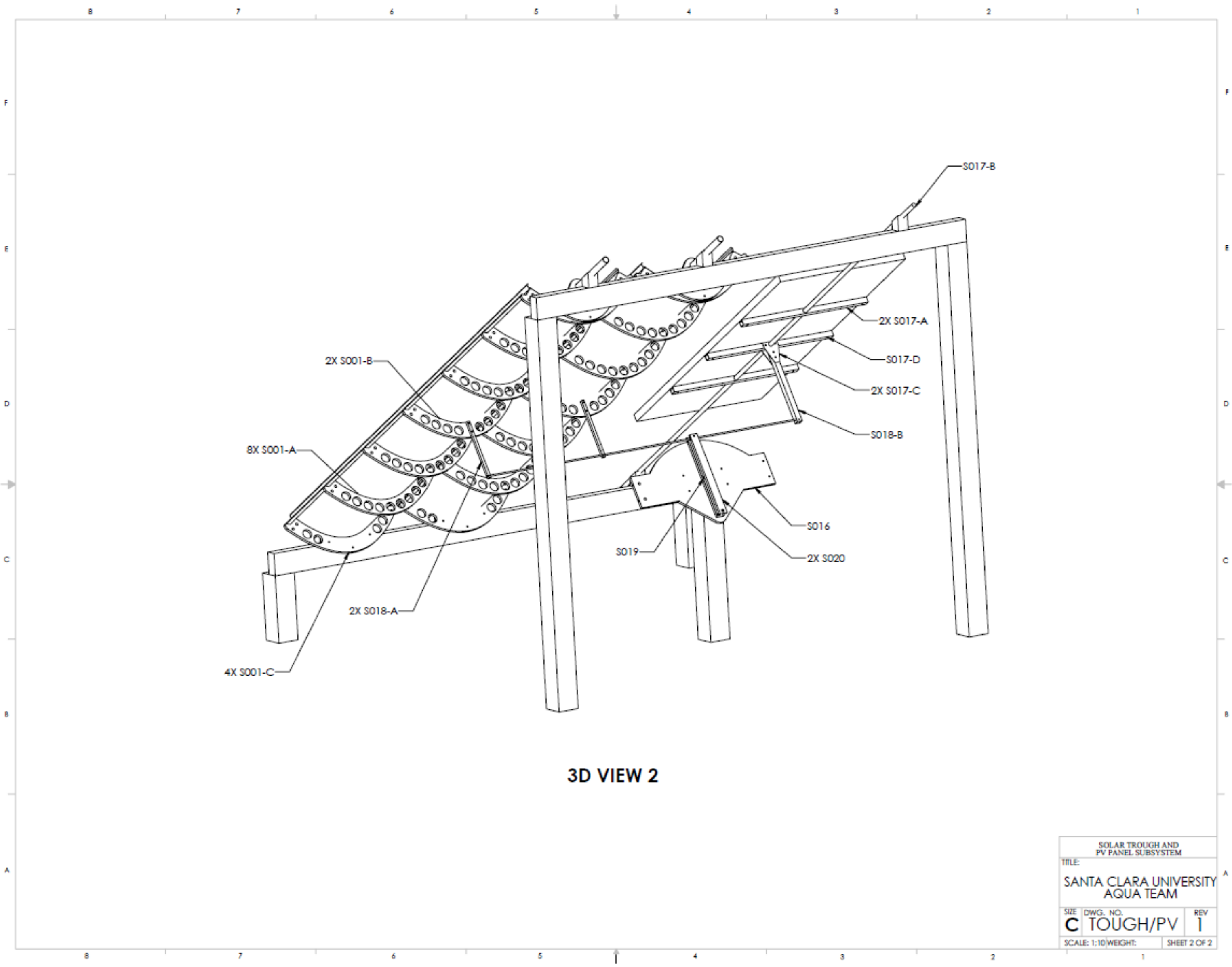

BOILER/HEAT EXCHANGER/CONDENSOR/CLEAN TANK SUBSYSTEM
3D VIEW 2
SOLAR POWERED WATER PURIFICATION SYSTEM
TITLE:
SANTA CLARA UNIVERSITY AQUA TEAM
SIZE DWG. NO. REV
C FULL SYSTEM 1
SCALE: 1:20 WEIGHT: SHEET 2 OF 3



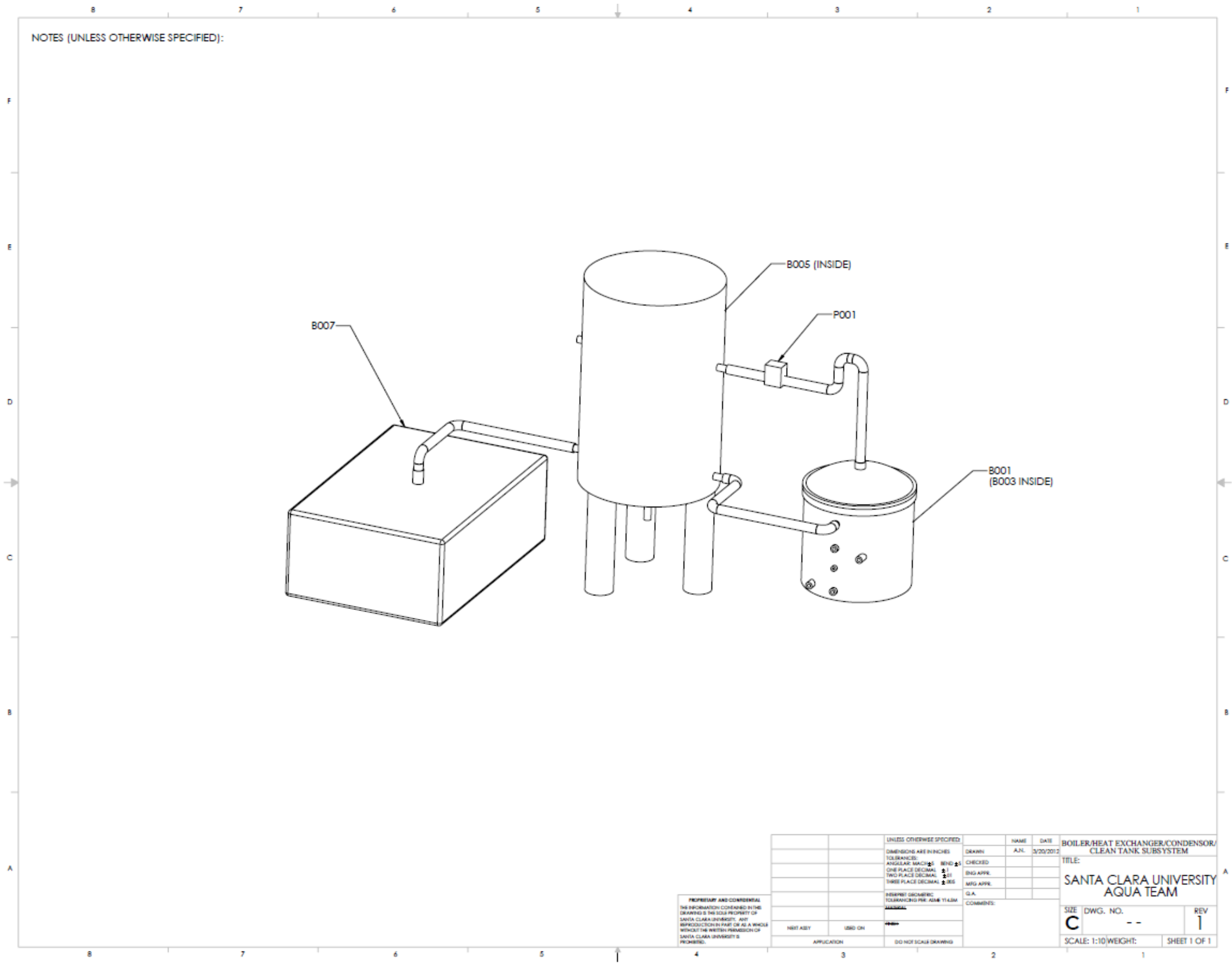
99.0
78.3
20.3
90.0
SOLAR POWERED WATER PURIFICATION SYSTEM
TITLE:
SANTA CLARA UNIVERSITY AQUA TEAM
SIZE DWG. NO. REV
C FULL SYSTEM 1
SCALE: 1:14 WEIGHT: SHEET 3 OF 3

B.3 Solar Trough and PV Assembly



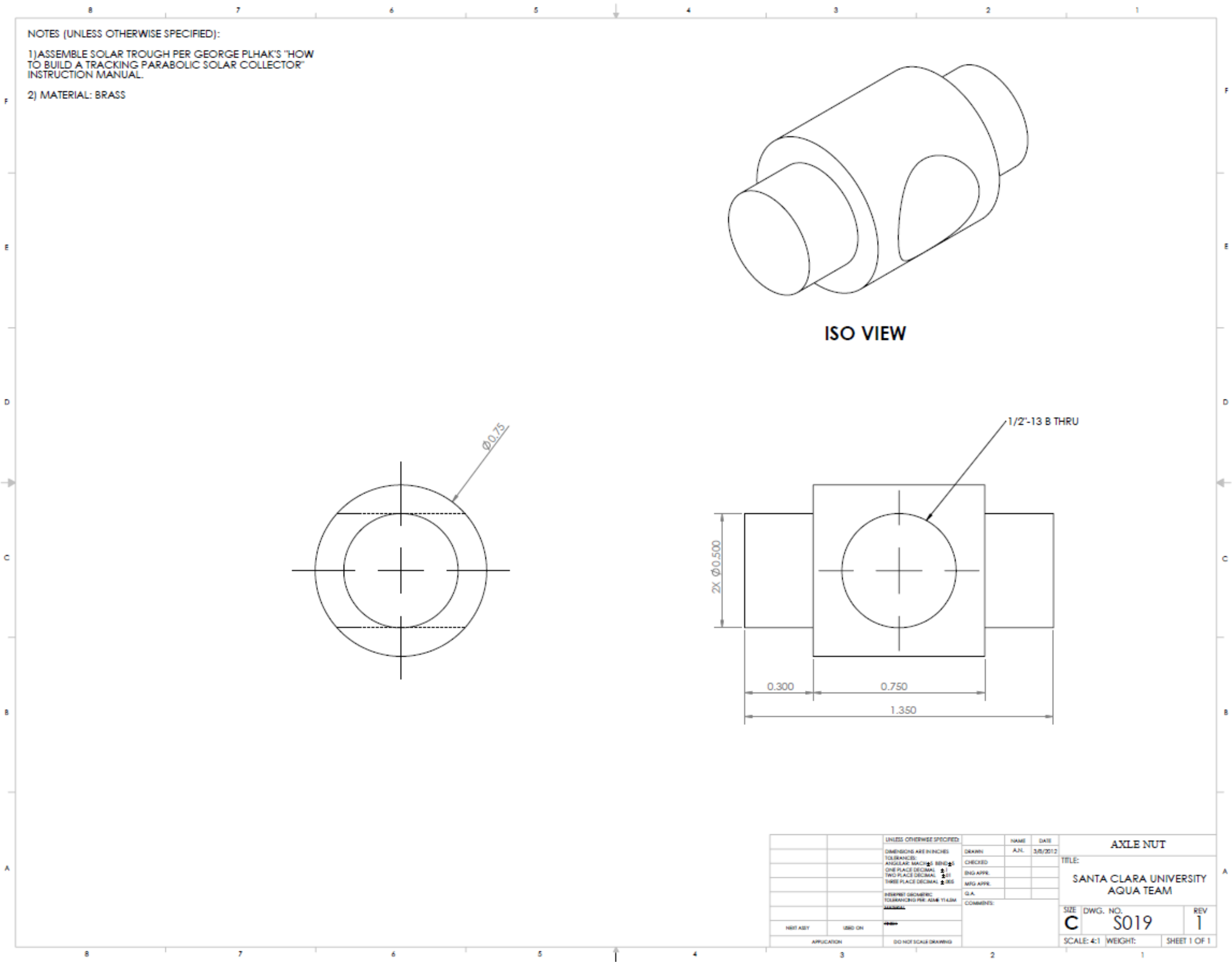

S017-B
2X S017-A
S017-D
2X S017-C
S018-B
2X S001-B
8X S001-A
S016
S019
2X S020
2X S018-A
4X S001-C
3D VIEW 2
SOLAR TROUGH AND PV PANEL SUBSYSTEM
TITLE:
SANTA CLARA UNIVERSITY AQUA TEAM
SIZE C
DWG. NO. TOUGH/PV
REV 1
SCALE: 1:10 WEIGHT:
SHEET 2 OF 2

B.4 Boiler, HEX, Condenser, and Clean Water Storage Tank Assembly

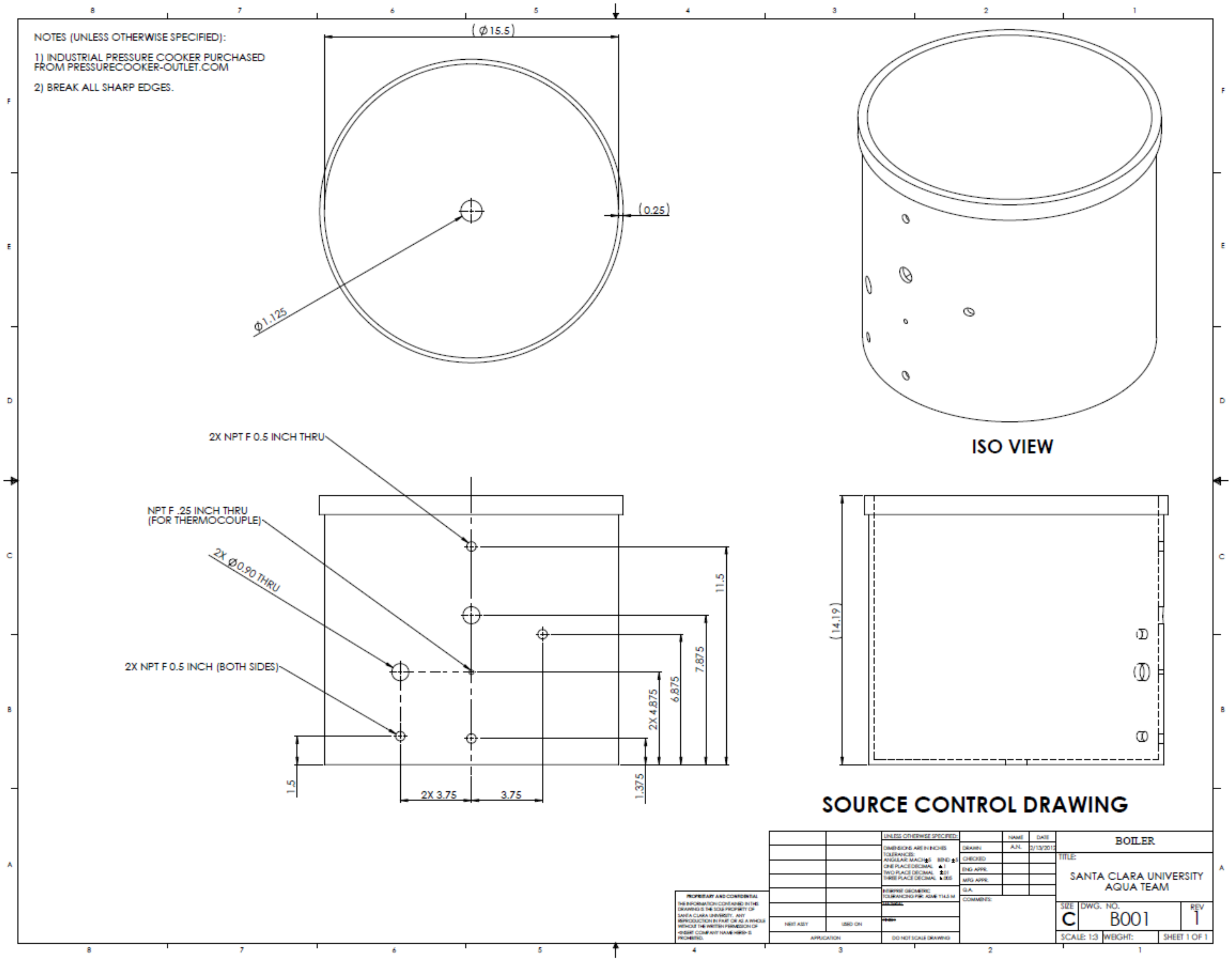


Appendix C: Assembly Drawings

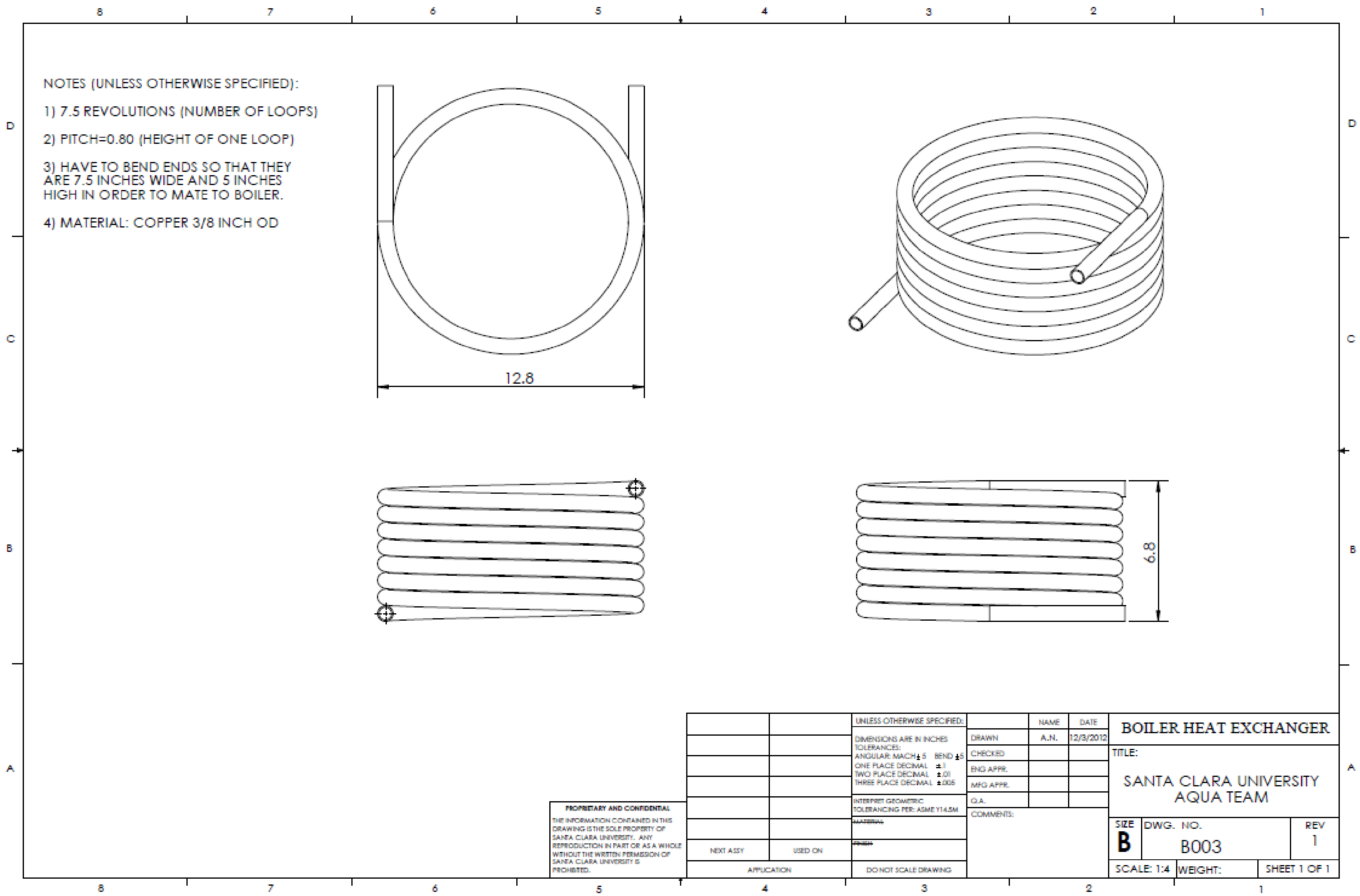
C.1 Axle Nut



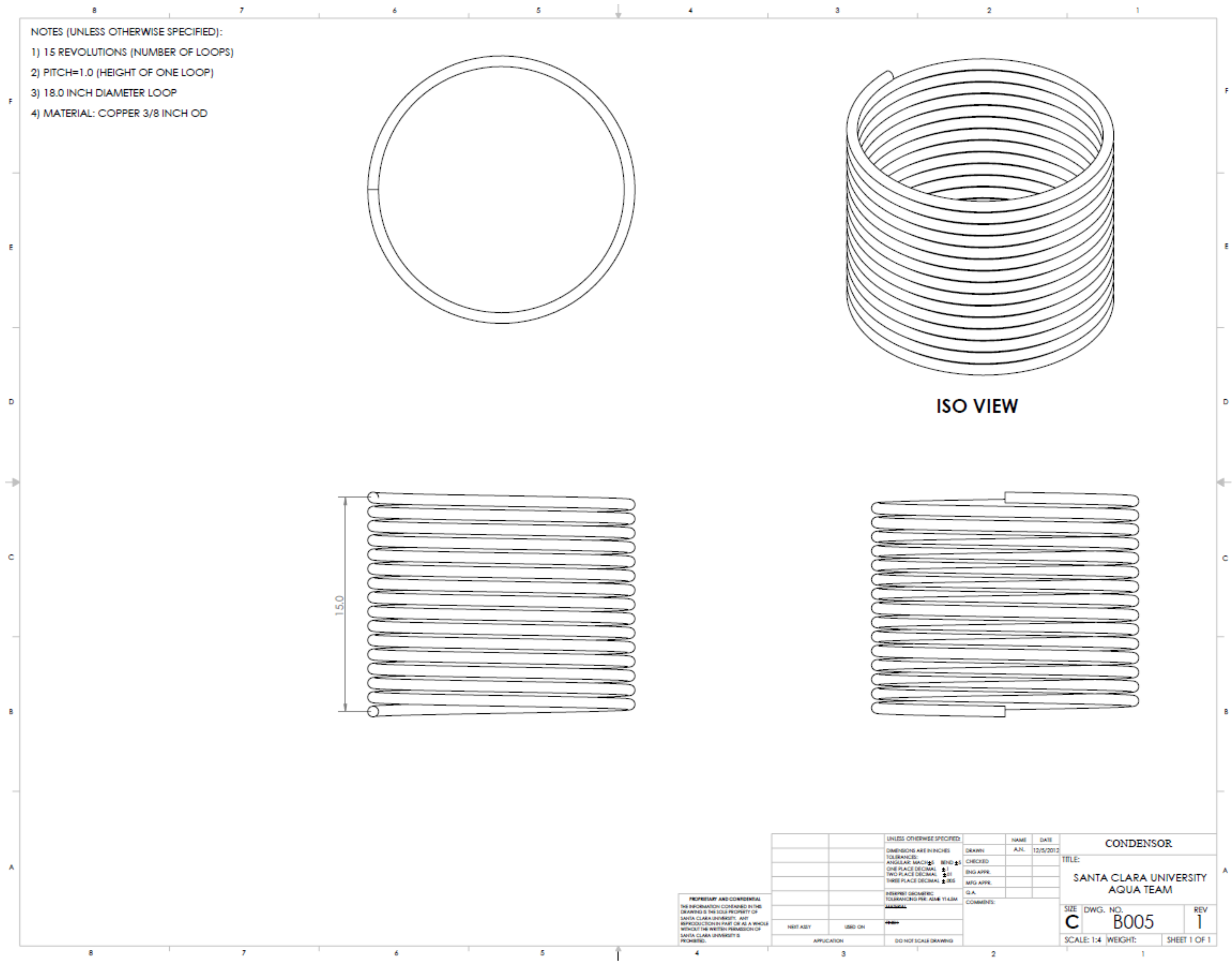
C.2 Boiler


NOTES (UNLESS OTHERWISE SPECIFIED):
1) INDUSTRIAL PRESSURE COOKER PURCHASED FROM PRESSURECOOKER-OUTLET.COM
2) BREAK ALL SHARP EDGES.
(Ø15.5)
(0.25)
Ø1.125
ISO VIEW
2X NPT F 0.5 INCH THRU
NPT F .25 INCH THRU (FOR THERMOCOUPLE)
2X Ø0.90 THRU
2X NPT F 0.5 INCH (BOTH SIDES)
11.5
7.875
6.875
2X 4.875
1.375
1.5
2X 3.75
3.75
(14.19)
SOURCE CONTROL DRAWING
BOILER
SANTA CLARA UNIVERSITY AQUA TEAM
C
B001
1
SCALE: 1:3
SHEET 1 OF 1

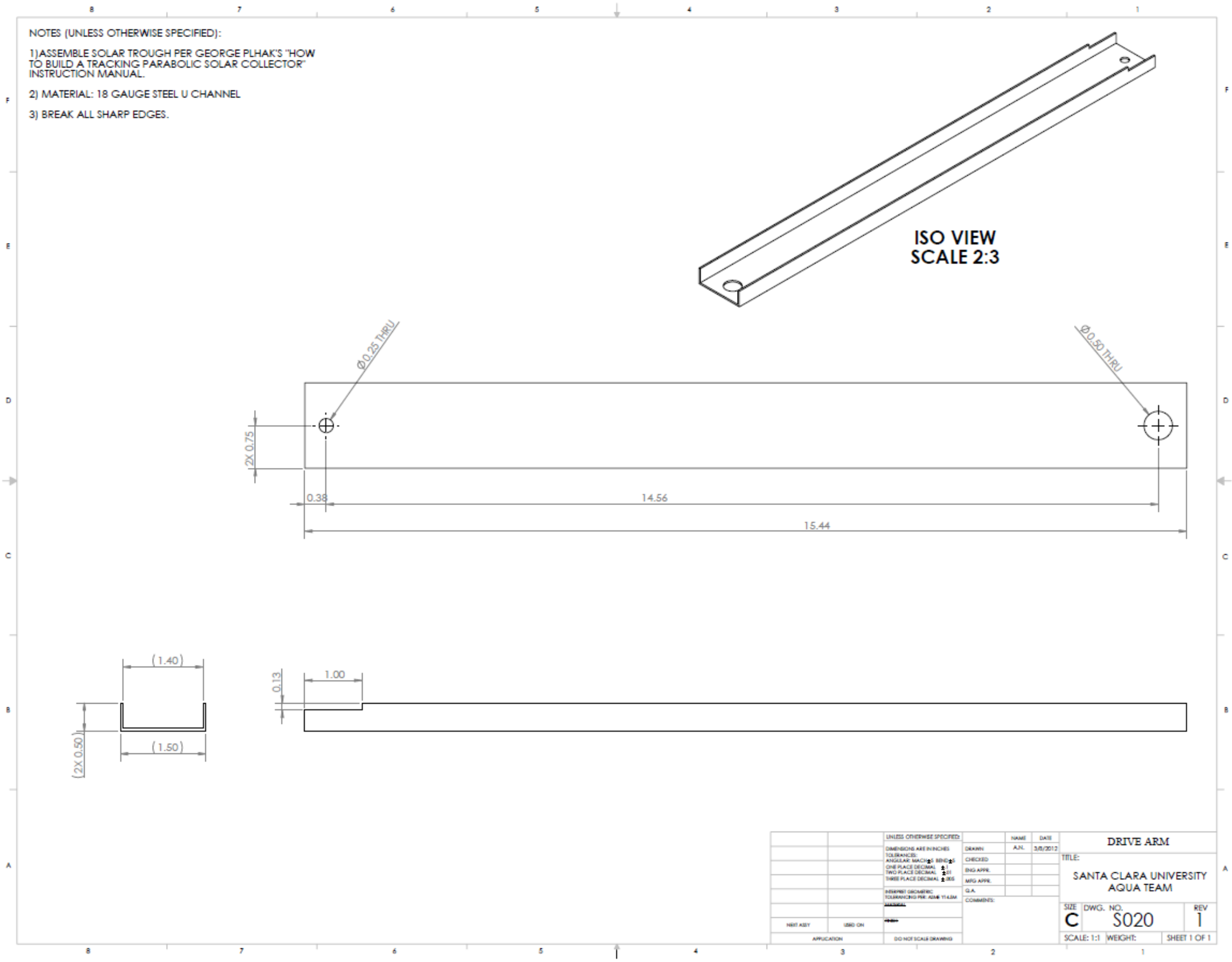
C.3 Boiler HEX



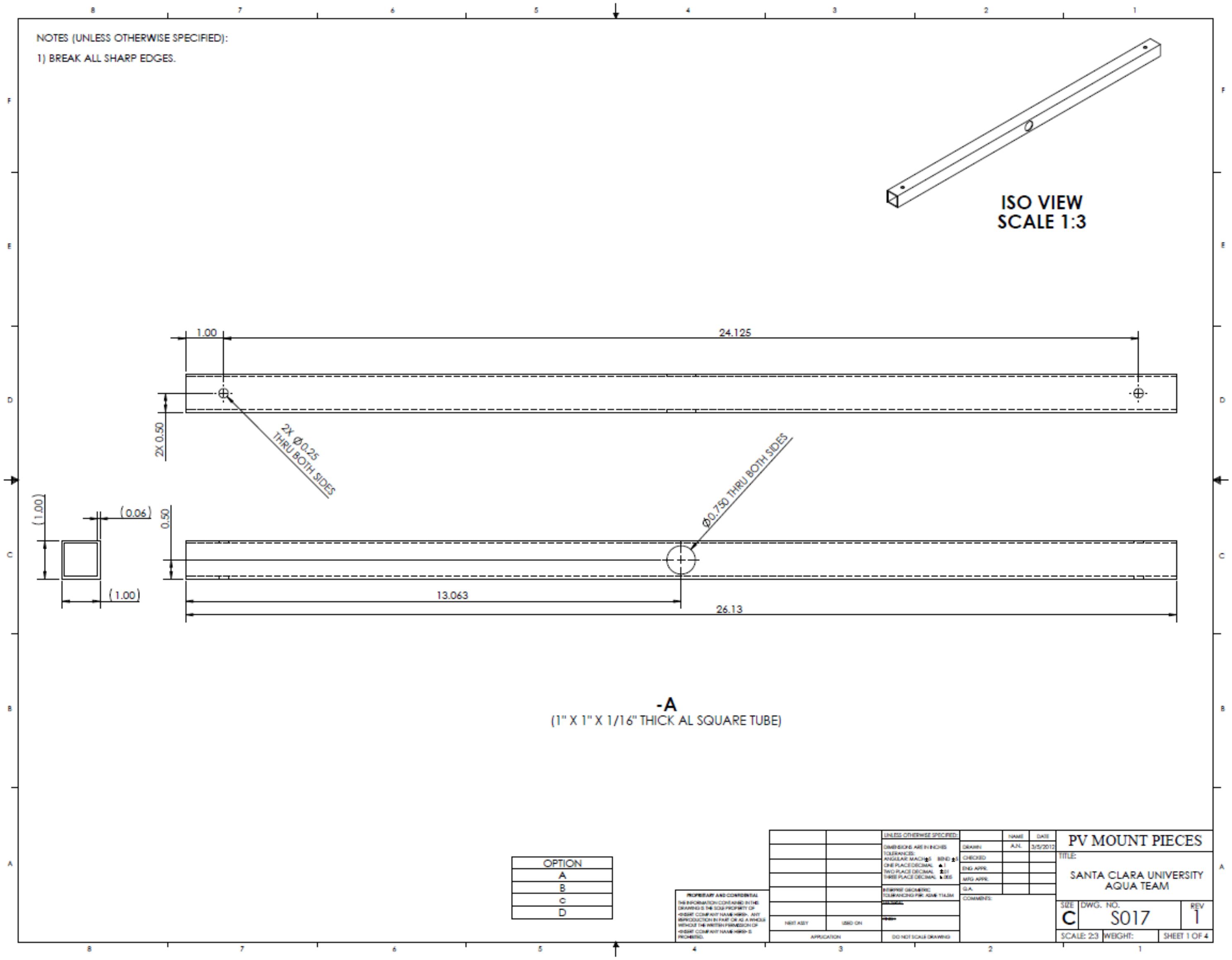
C.4 Condenser

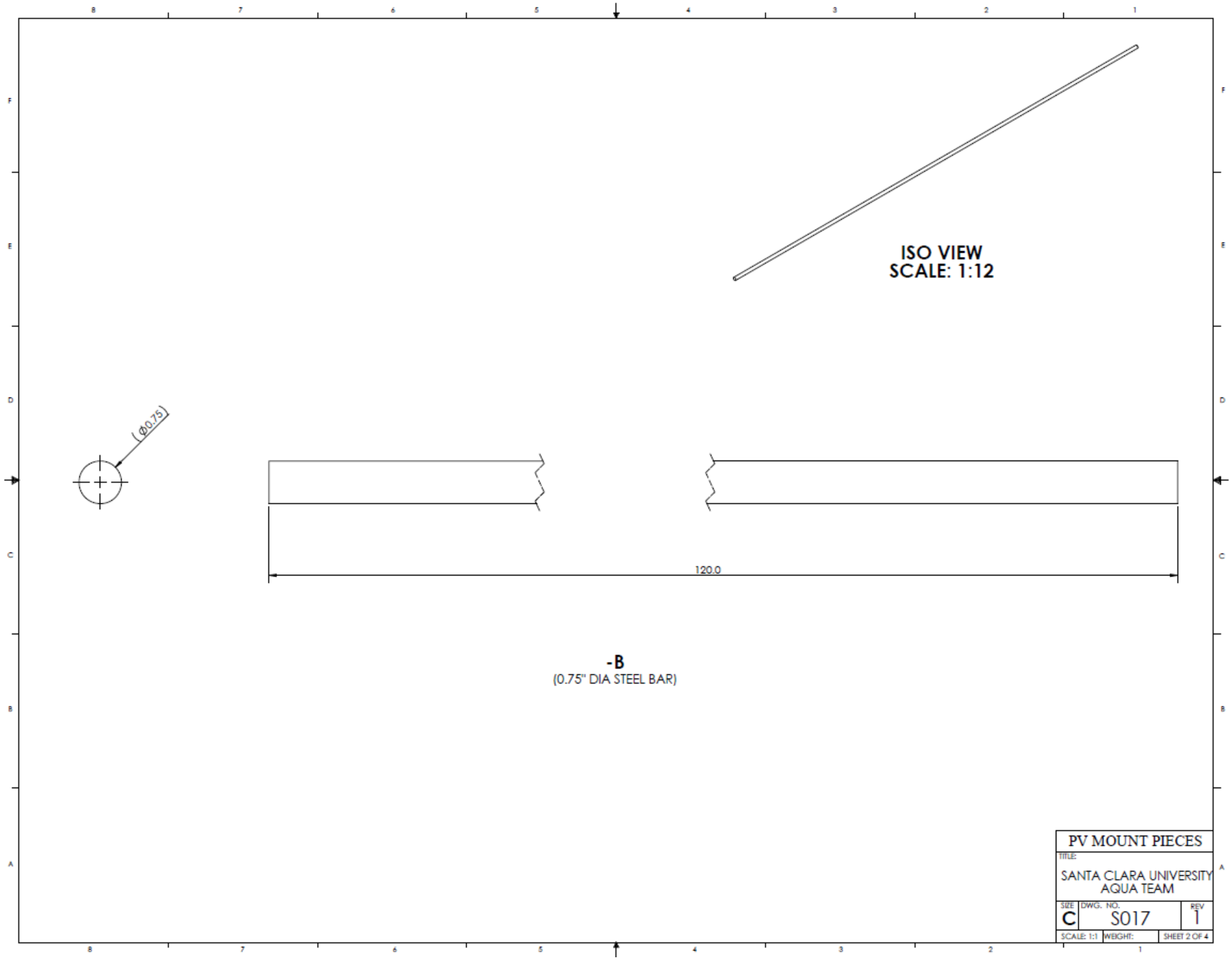


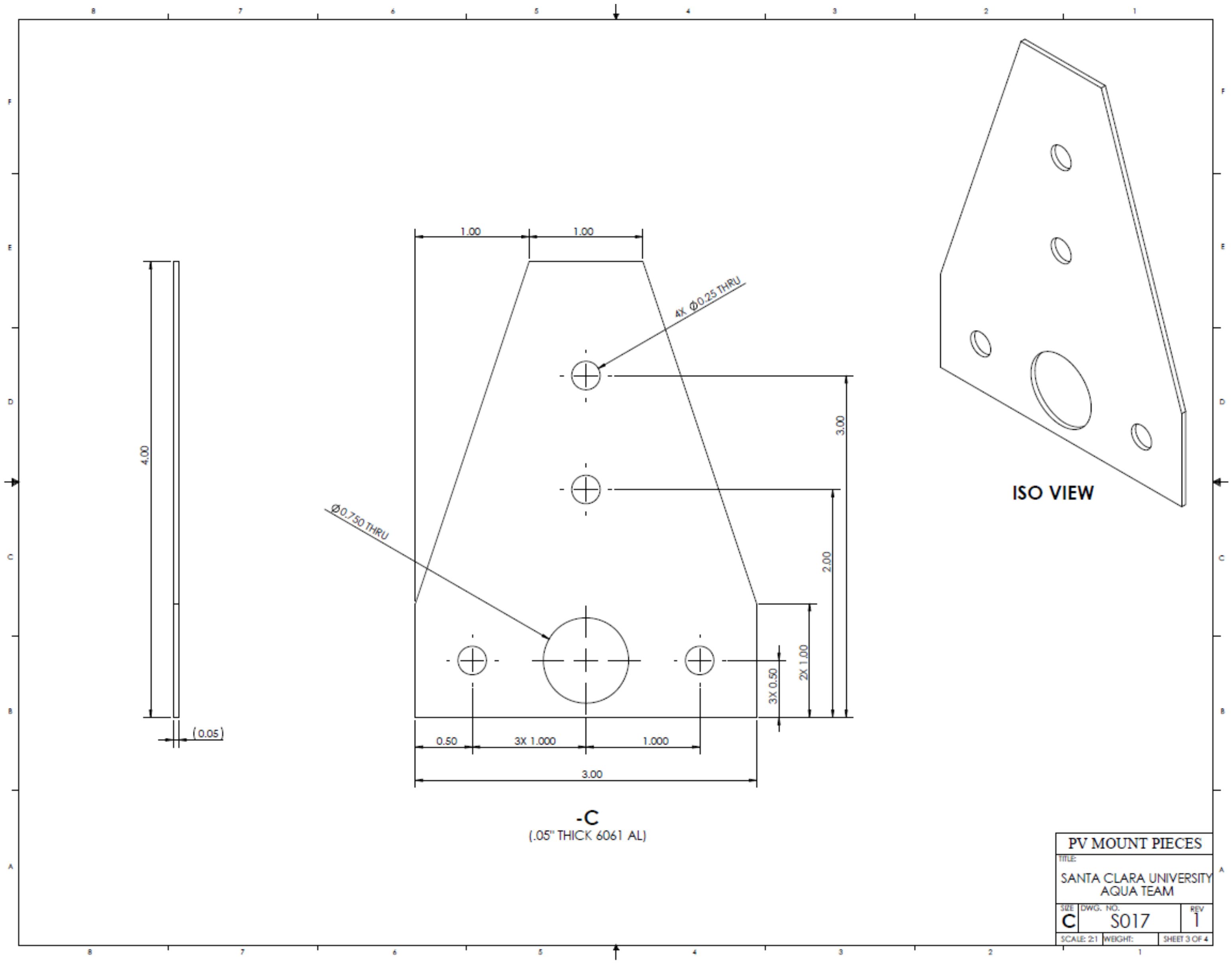
C.5 Drive Arm

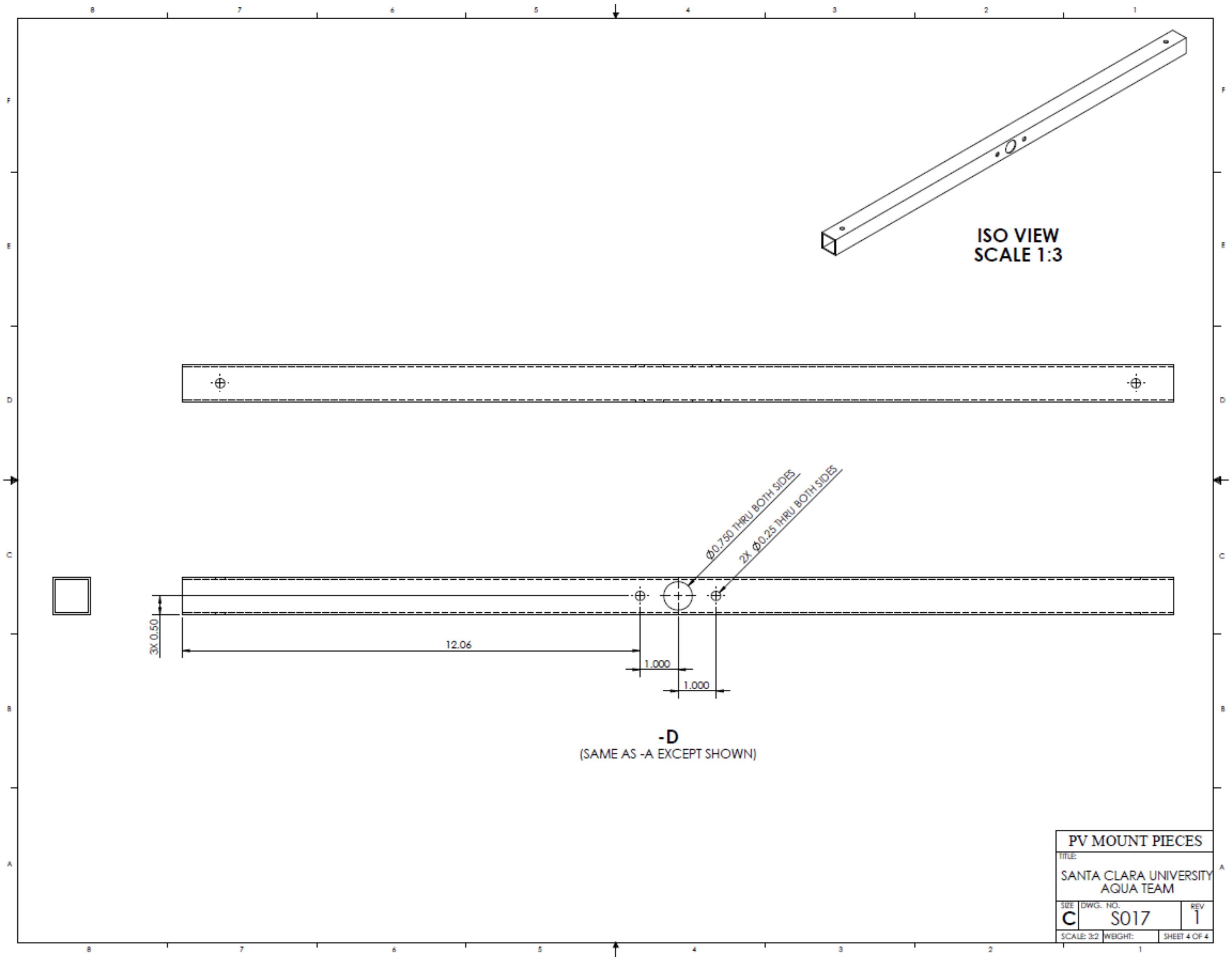

NOTES (UNLESS OTHERWISE SPECIFIED):
1)ASSEMBLE SOLAR TROUGH PER GEORGE PLHAK'S "HOW TO BUILD A TRACKING PARABOLIC SOLAR COLLECTOR" INSTRUCTION MANUAL.
2) MATERIAL: 18 GAUGE STEEL U CHANNEL
3) BREAK ALL SHARP EDGES.
ISO VIEW
SCALE 2:3
Ø0.25 THRU
Ø0.50 THRU
2X 0.75
0.38
14.56
15.44
(1.40)
(1.50)
(2X 0.50)
0.13
1.00
DRIVE ARM
SANTA CLARA UNIVERSITY
AQUA TEAM
C
S020
1
SCALE: 1:1
SHEET 1 OF 1

C.6 PV Mount Pieces

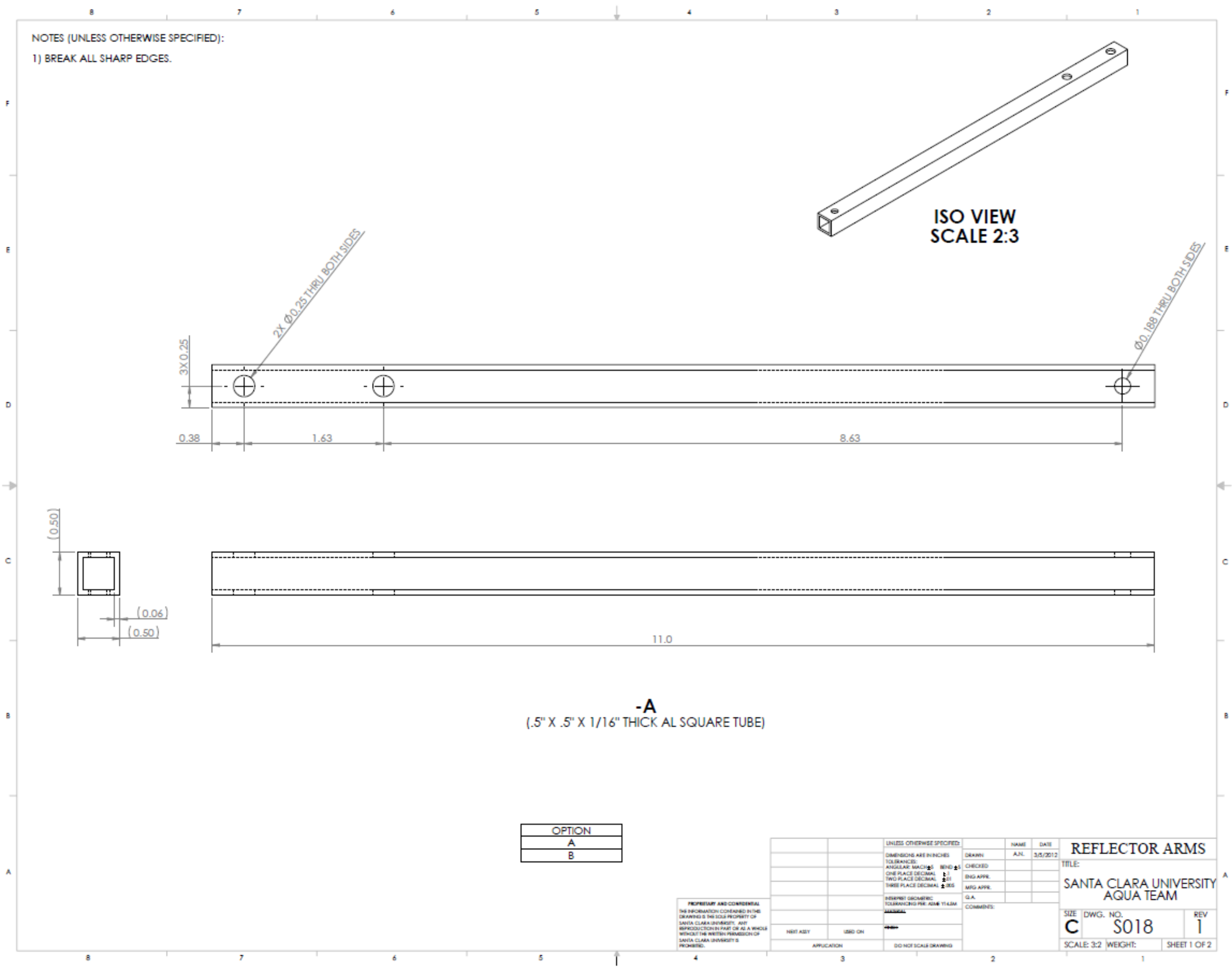


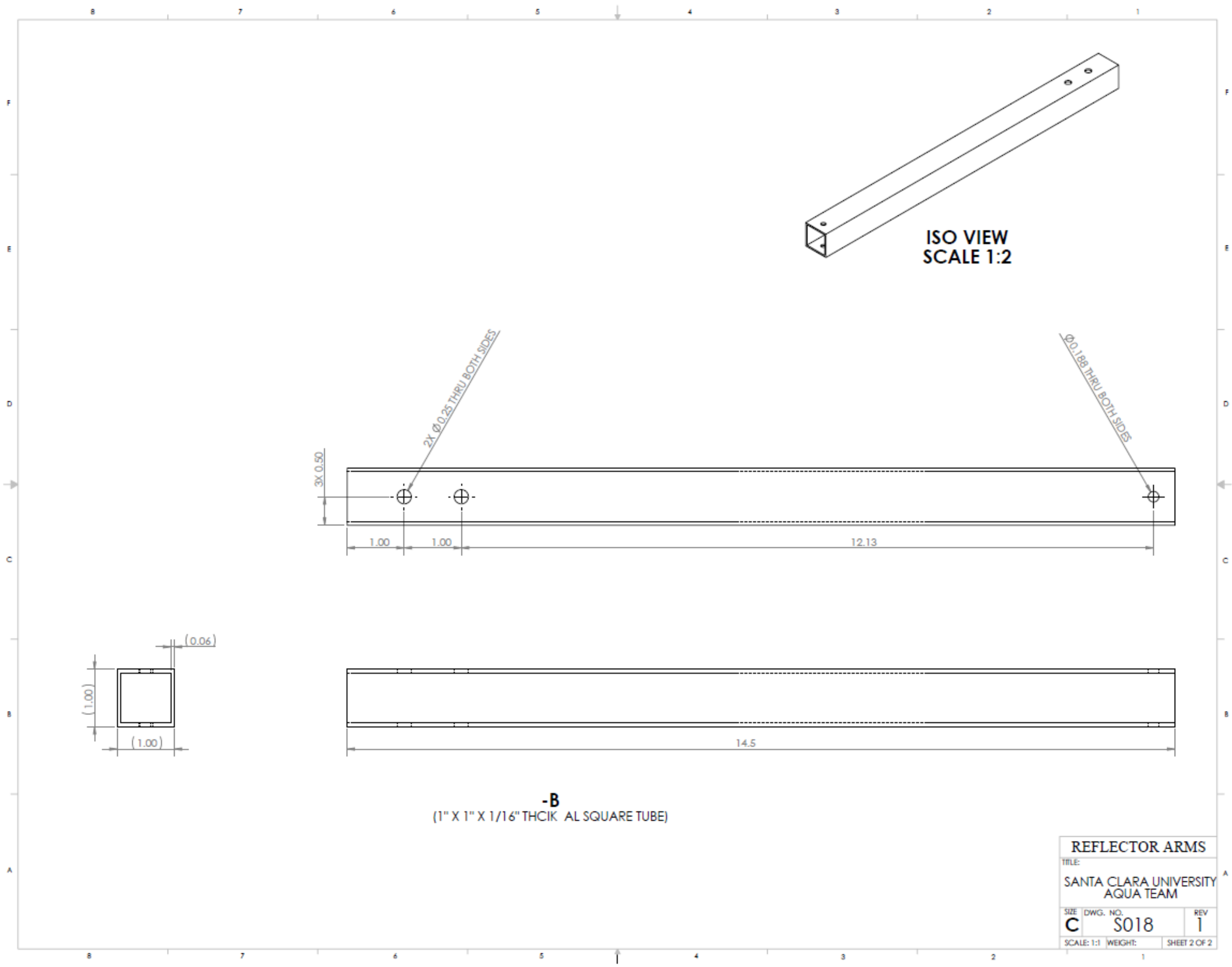

ISO VIEW
SCALE: 1:12
(Ø0.75)
120.0
-B
(0.75" DIA STEEL BAR)
PV MOUNT PIECES
TITLE:
SANTA CLARA UNIVERSITY
AQUA TEAM
SIZE
C
DWG. NO.
S017
REV
1
SCALE: 1:1
WEIGHT:
SHEET 2 OF 4


1.00
1.00
4X Ø0.25 THRU
Ø0.750 THRU
4.00
3.00
2.00
2X 1.00
3X 0.50
(0.05)
0.50
3X 1.000
1.000
3.00
ISO VIEW
-C
(.05" THICK 6061 AL)
PV MOUNT PIECES
TITLE:
SANTA CLARA UNIVERSITY
AQUA TEAM
SIZE
C
DWG. NO.
S017
REV
1
SCALE: 2:1
WEIGHT:
SHEET 3 OF 4

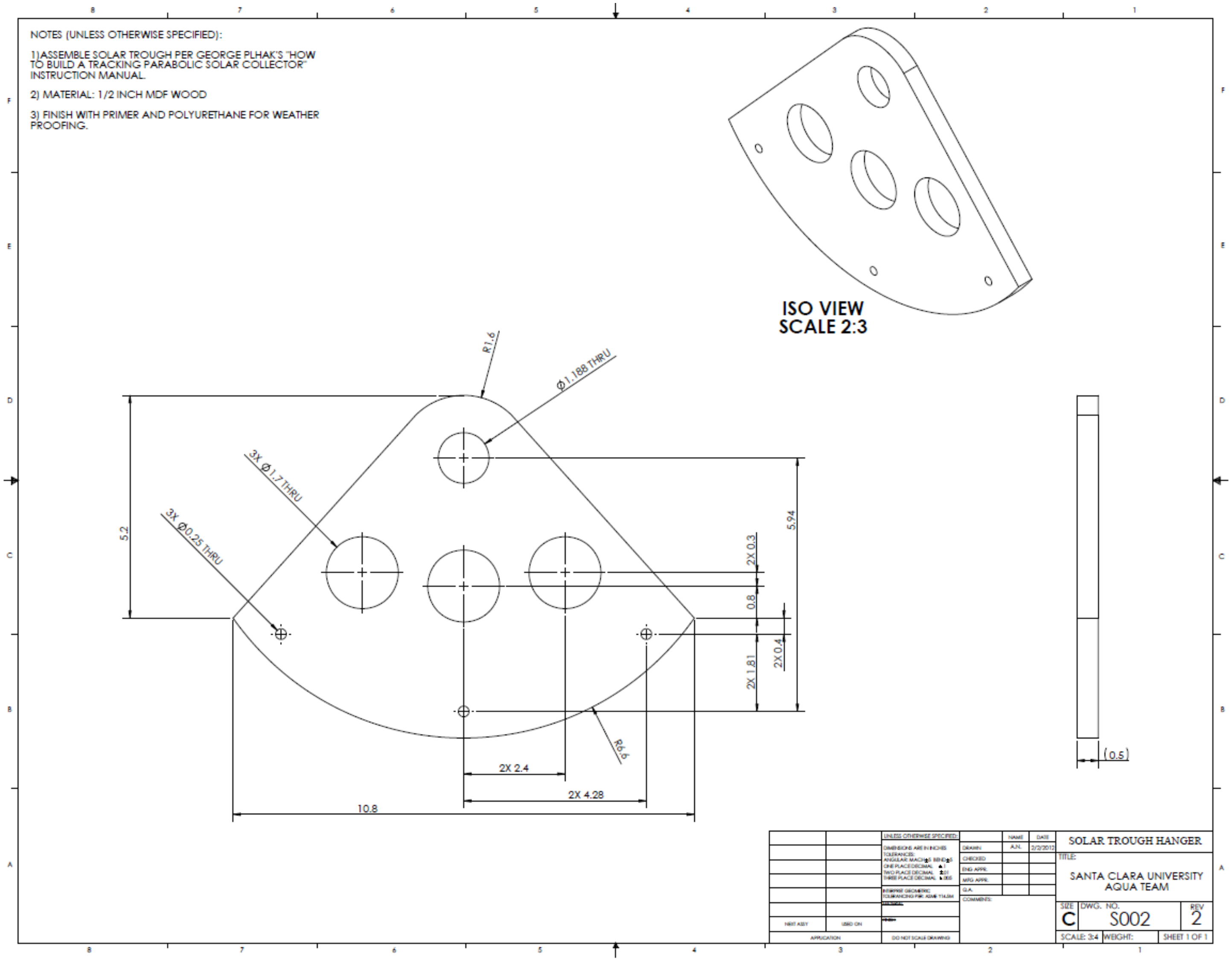

ISO VIEW
SCALE 1:3
Ø0.750 THRU BOTH SIDES
2X Ø0.25 THRU BOTH SIDES
3X 0.50
12.06
1.000
1.000
-D
(SAME AS -A EXCEPT SHOWN)
PV MOUNT PIECES
TITLE:
SANTA CLARA UNIVERSITY
AQUA TEAM
SIZE
C
DWG. NO.
S017
REV
1
SCALE: 3:2
WEIGHT:
SHEET 4 OF 4

C.7 Reflector Arms

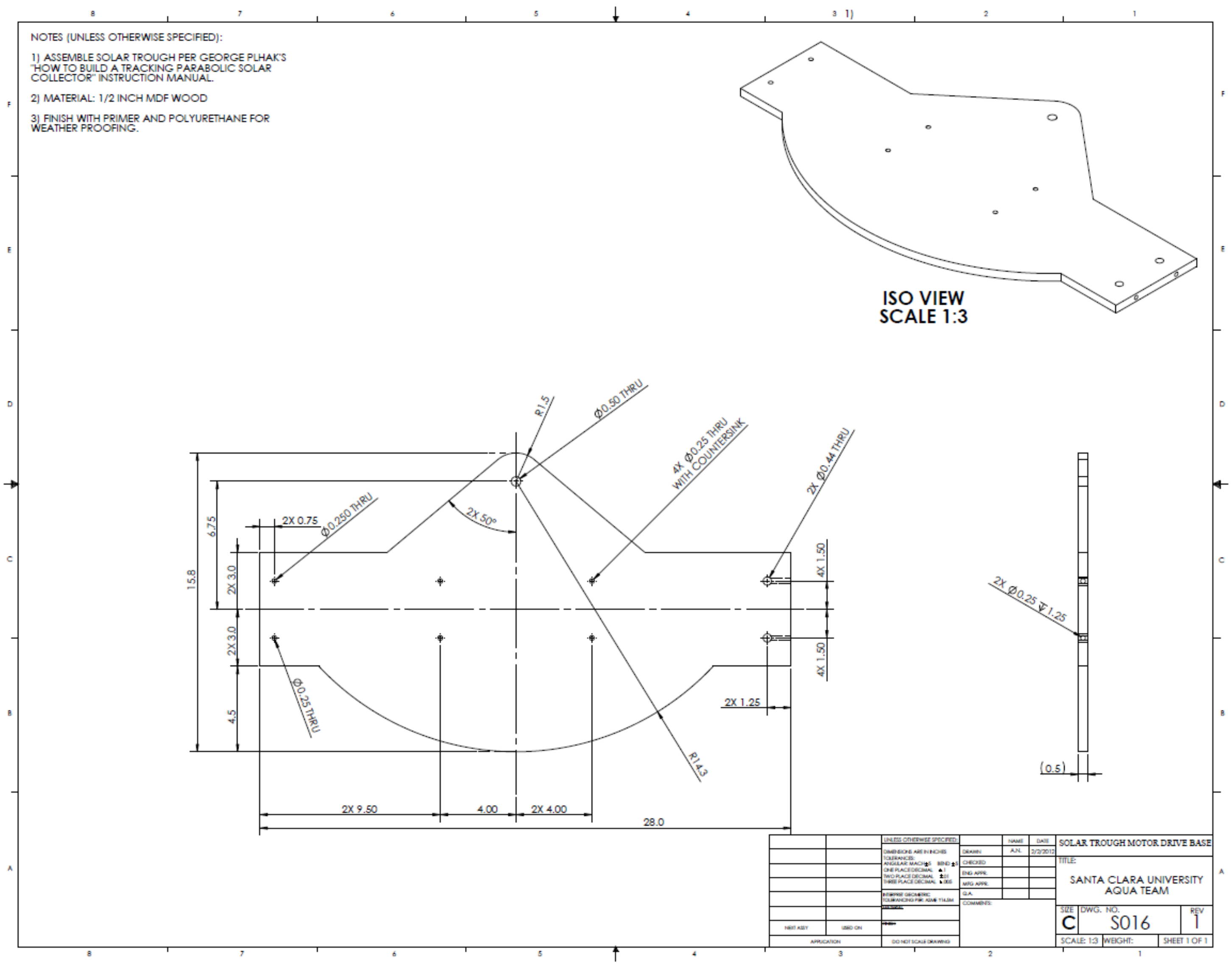



ISO VIEW
SCALE 1:2
2X Ø0.25 THRU BOTH SIDES
Ø0.188 THRU BOTH SIDES
3X 0.50
1.00
1.00
12.13
(0.06)
(1.00)
(1.00)
14.5
-B
(1" X 1" X 1/16" THCIK AL SQUARE TUBE)
REFLECTOR ARMS
TITLE:
SANTA CLARA UNIVERSITY
AQUA TEAM
SIZE
C
DWG. NO.
S018
REV
1
SCALE: 1:1
WEIGHT:
SHEET 2 OF 2

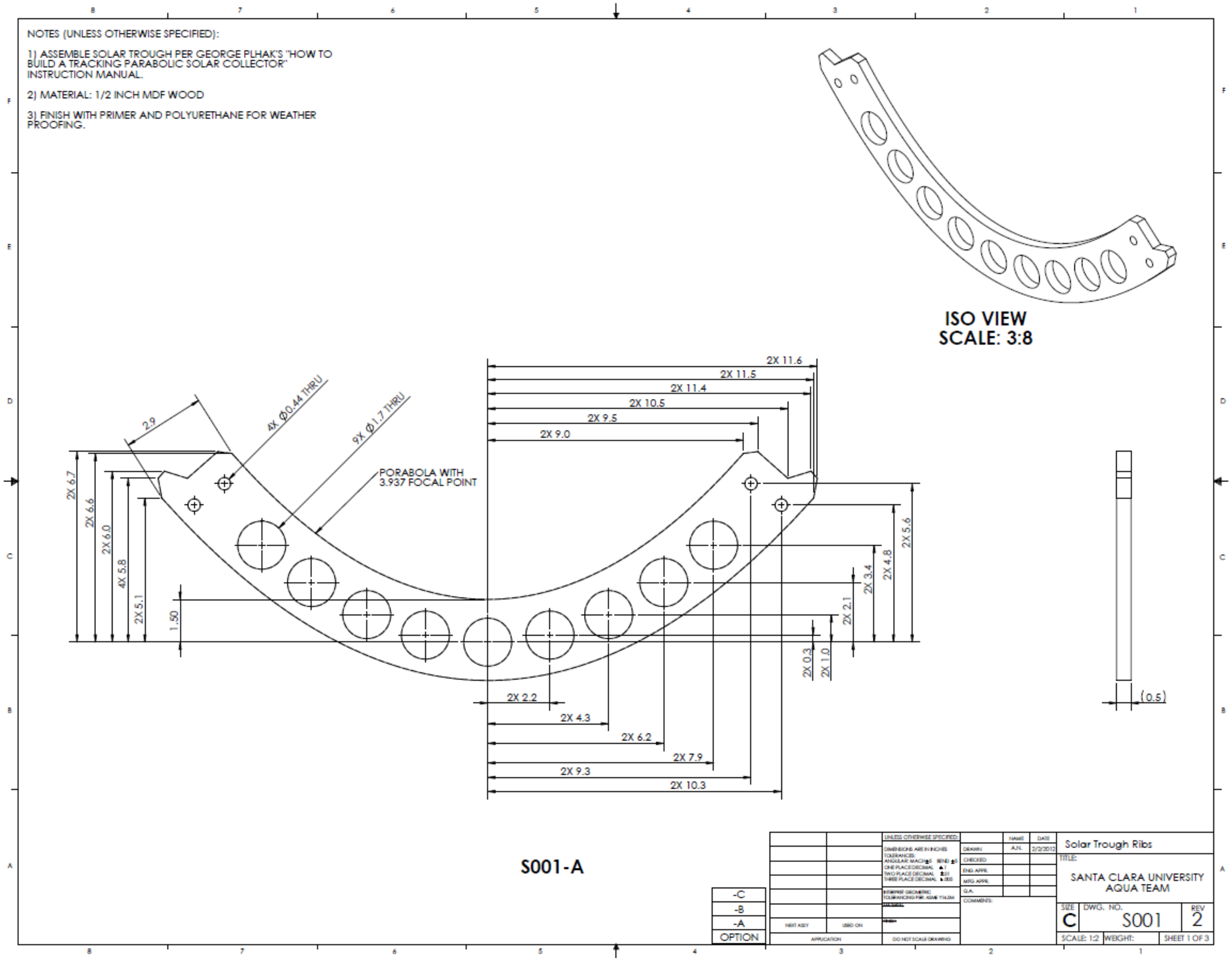
C.8 Solar Trough Hanger

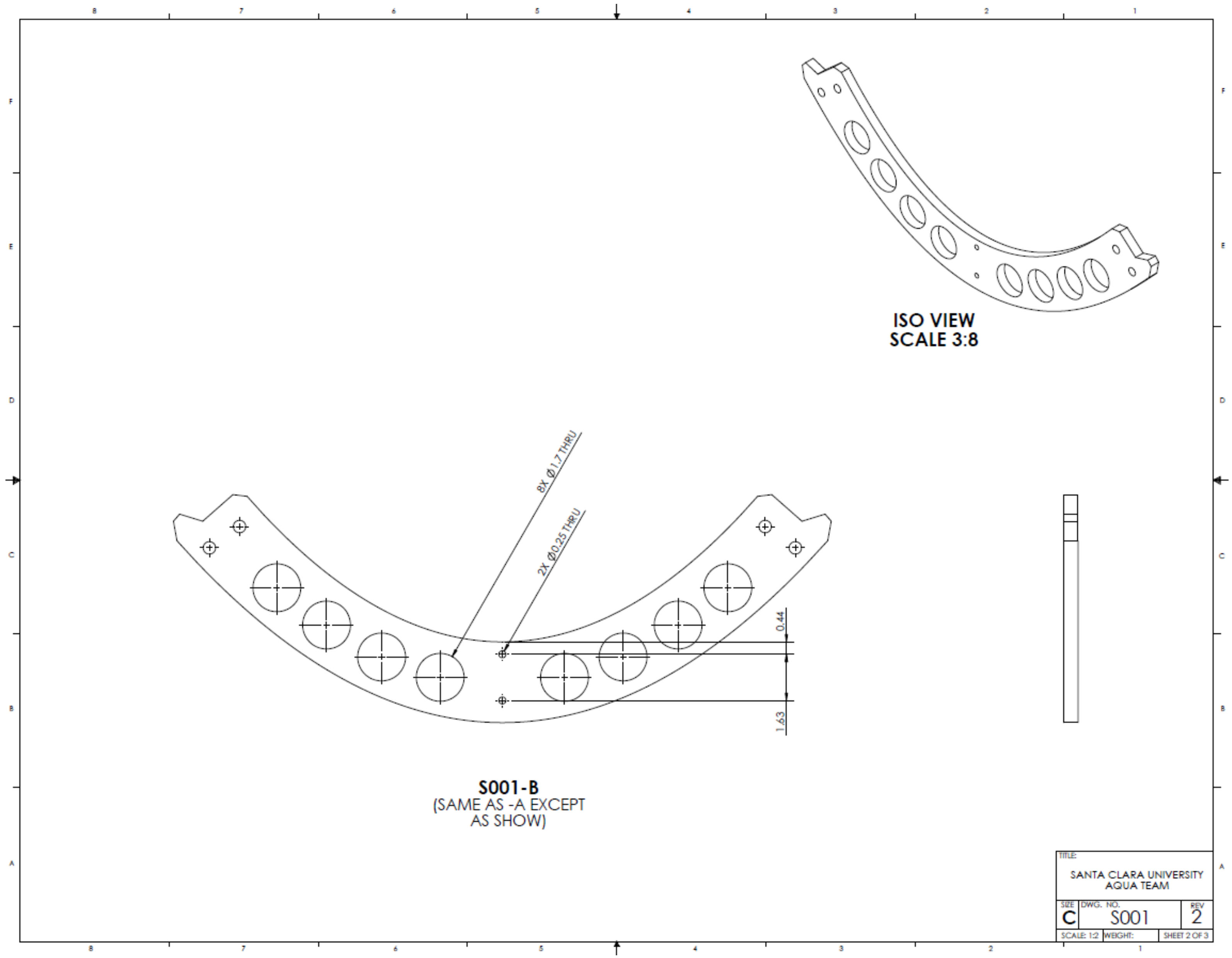


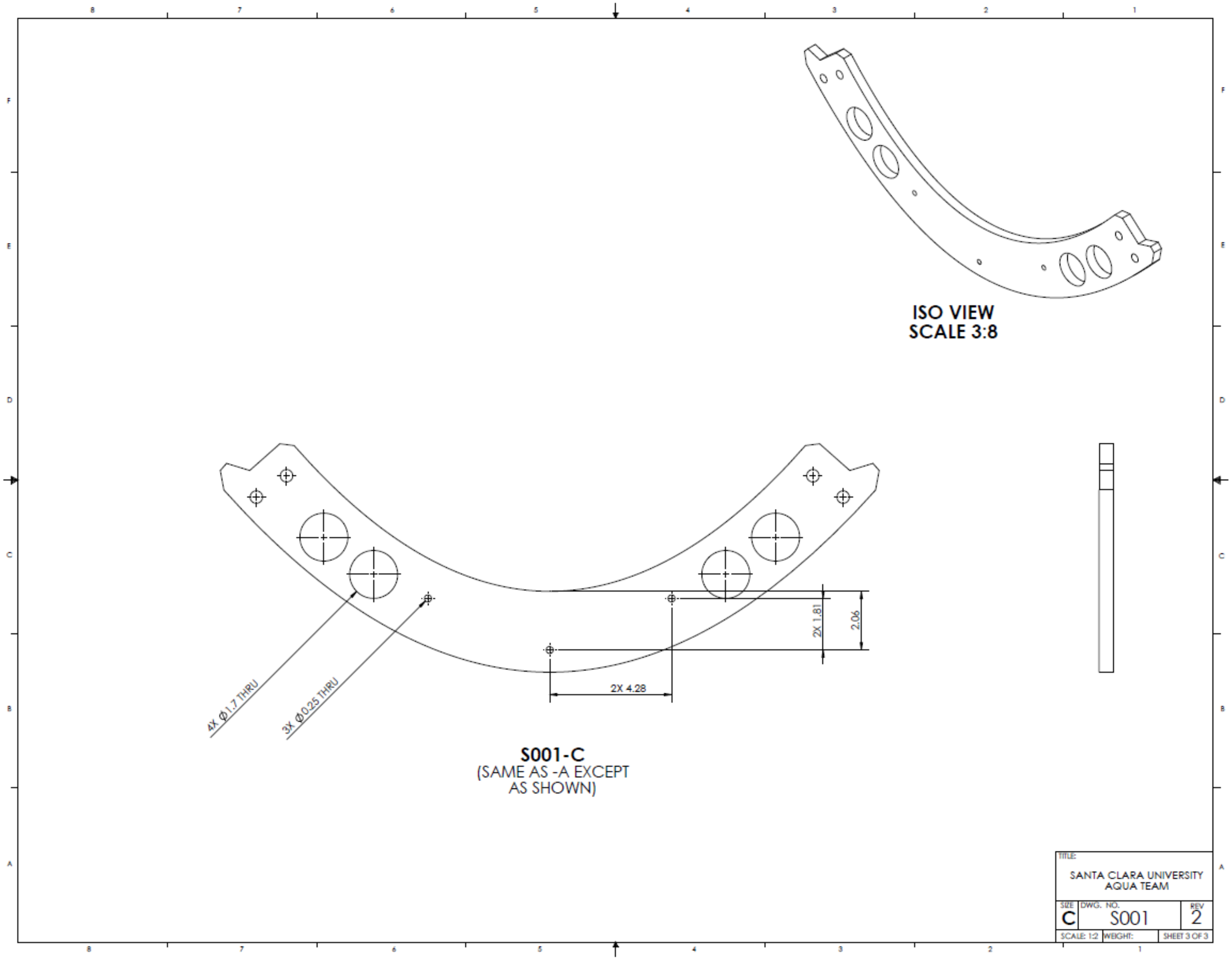
C.9 Solar Trough Motor Drive Base



C.10 Solar Trough Ribs




ISO VIEW
SCALE 3:8
8X Ø1.7 THRU
2X Ø0.25 THRU
0.44
1.63
S001-B
(SAME AS -A EXCEPT
AS SHOW)
TITLE:
SANTA CLARA UNIVERSITY
AQUA TEAM
SIZE C
DWG. NO. S001
REV 2
SCALE: 1:2
WEIGHT:
SHEET 2 OF 3


ISO VIEW
SCALE 3:8
4X Ø1.7 THRU
3X Ø0.25 THRU
2X 4.28
2X 1.81
2.06
S001-C
(SAME AS -A EXCEPT
AS SHOWN)
TITLE:
SANTA CLARA UNIVERSITY
AQUA TEAM
SIZE
C
DWG. NO.
S001
REV
2
SCALE: 1:2
WEIGHT:
SHEET 3 OF 3

Appendix D: Detailed Equations (Engineering Equation Solver)

D.1 Total System Level

```
"*****************************************************************************************************
SYSTEM LEVEL
*****************************************************************************************************"

"SYSTEM PROPERTIES
*****************************************************************************************************"

g = 9.81 [m/s^2]
k_2 = 400 * 10^(-3)                          {conductivity of copper [kW/(m*K)]}
P_1 = 100 [kPa]
sigma_1 = 5.670 * 10^(-11)                   {stefan-boltzmann}
q_flux_2 = 0.850 [kW/m^2]                    {energy from the sun}
T_1 = 30 {C} + 273                           {atmospheric temp}

"SALT WATER ***************************************************************************************"
T_7= 25 {C} + 273                            {assumed inlet temperature of water to boiler}
m_1 = V_1 * rho_6                            {mass of sw in boiler}

"WATER AND VAPOR *********************************************************************************"
beta_3 = 0.042 [1/K]                         {thermal expansion of water}
Cp_2 = specheat(water, P=P_1, x=0)           {specific heat of liquid water}
dh_1 = he_2 - he_1                           {latent heat of vaporization of water evaporating}
he_1 = enthalpy(Water,P=P_1,x=0)
he_2 = enthalpy(Water,P=P_1,x=1)
k_1 = 0.668*10^(-3)                          {conductivity, water at 70 C [kW/(m*K)]}
m_dot_2 = V_dot_1 * rho_1                    {mass flow rate of vapor kg/s}
mu_3 = viscosity(water, P=P_1, x=0)          {dynamic viscosity of water}
Pr_3 = prandtl(water, P=P_1, x=0)            {prandtl number of water}
rho_1 = density(water, P=P_1, x=1)           {density of vapor}
rho_6 = density(water, T=T_7, P=P_1)
T_6 = temperature(water, P=P_1, x=1)
V_dot_1 = V_dot_2 / 951019.4                 {volumetric flow rate of vapor, m^3/s}
V_dot_2 = 1 [gal/hr]                         {desired volumetric flow rate of vapor, gal/hr}

"AIR **********************************************************************************************"
beta_1 = 3.2 * 10^(-3)                       {coeff of volume expansion of air}
k_4 = 0.024 * 10^(-3)                        {thermal conductivity of air  [kW/(m*K)]}
mu_2 = viscosity(air,T=T_1)                  {dynamic viscosity of air}
Pr_2 = prandtl(air,T=T_1)
rho_3 = density(air, P=P_1, T=T_1)
Vel_2 = 1 [m/s]                              {velocity of air over troughs}

"HTF - DURATHERM **********************************************************************************"
Cp_1 = 2.386 [kJ/kg*K]                       {specific heat of HTF}
k_3 = 0.137 * 10^(-3)                        {thermal conductivity of HTF}
m_dot_1 = 0.11 [kg/s]                        {mass flow rate of HTF}
mu_1 = nu_1 * rho_2                          {dynamic viscosity}
nu_1 = 1.3 * 10^(-6)                         {kinematic viscosity m^2 / s}
Pr_1 =  Cp_1 * mu_1 / k_3                    {prandtl}
rho_2 = 793 [kg/m^3]                         {density of HTF}
spv_1 = 1/rho_2                              {specific volume of HTF}
```

```
T_avg_1 = (T_4+ T_3)/2                          {avg temp of HTF in boiler}
T_avg_2 = (T_2 + T_3)/2                         {avg temp of HTF in trough}
V_dot_3= m_dot_1 * spv_1                        {volumetric flow rate of HTF, m^3/s}
V_dot_4 = V_dot_3 *951019.4 [gal/hr]            {volumetric flow rate of HTF, gal/hr}

"*******************************************************************************************************
HELICAL BOILER
*******************************************************************************************************"

"SUBSYSTEM PARAMETERS*************************************************************************"
k_5 = 0.250 [kW/(m * K)]                        {thermal conductivity of boiler material -
aluminum}

Q_1 = m_dot_1 * Cp_1 * (T_3-T_4)                {solves for T_4}

"GEOMETRIES*************************************************************************************"

"Boiler"
A_o_2 = pi*d_5 * ht_3                           {outer surface area of boiler}
d_4 =15.5 {in} * 0.0254                         {inner diameter of boiler}
d_5 = 16.25 {in} * 0.0254                       {outer diameter of boiler}
ht_2 =7 {in} * 0.0254                           {height of salt water in boiler}
ht_3 = 18 {in} * 0.0254                         {height of boiler}
V_1 = ht_2 * (pi/4) * (d_4)^2                   {volume of salt water in boiler}

"HEX"
A_c_1 = pi/4 * (d_1)^2                          {cross sectional area of HEX pipe}
A_i_1 = L_1 * d_1 * pi                          {total inner surface area of the coil HEX}
A_o_1 = L_1 * d_2 * pi                          {total outer surface area of the helical HEX}
c_1 = pi * d_3                                  {circumference of one loop of the helical HEX}
d_1 = 0.311 {in} * 0.0254                       {0.0254 m/in}  {inner diameter of HEX tubing}
d_2= (3/8) {in} * 0.0254                        {outer diameter of HEX tubing}
d_3 = (12 + 3/8) {in} * 0.0254                  {diameter of one loop of the helical HEX}
ht_1 = 1 {in} * 0.0254                          {height of one loop of the helical HEX}
L_1 = ((ht_1^2) + (c_1^2))^0.5 * n_1            {total length of the helical HEX}
n_1 = 8

"HEAT TRANSFER FROM HEX to SW -- CHOOSE NUCLEATE BOILING OR NATURAL CONVECTION
REGIME*****"

"From HEX"
Vel_1 = (m_dot_1 * spv_1) / A_c_1               {velocity of HTF in HEX}
Re_1 = (Vel_1 * d_1) / nu_1                     {Reynolds number}

Nusselt_1 = 0.023 * (Re_1)^(4/5) * (Pr_1)^0.3   {assumed turbulent}
h_1 = (Nusselt_1 * k_3) / d_1                   {heat transfer coefficient}

R_1 = 1/(h_1 * A_i_1)                           {convective resistance between HTF and HEX
inner surface}
R_2 = ln((d_2/2)/(d_1/2)) / (k_2 * 2 * pi * L_1)  {conduction resistance through HEX}

Q_1 = (T_avg_1 - T_8) / (R_1 + R_2)             {Heat provided by HEX, solves for T_8(surface
temp)}
```

```
"To Saltwater"

    "IF Nucleate Boiling"

q"_s=Nucleate_Boiling(Fluid$, T_sat, T_w, C_s_f)
    Fluid$ = 'Water'
    T_sat = T_6
    T_w = T_8                                    {HEX surface temperature}
    C_s_f = 0.0068                               {from pg 628 of Heat Transfer book, scored
water-copper}

q_flux_1 = q"_s / 1000                           {converts from W to kW}
Q_1 = q_flux_1 * A_o_1                           {Heat provided by HEX}

{=========================================================================
"IF natural convection (ramp up)"

Gr_1 = (d_2^3 * rho_6^2 * g * (T_8 - T_7) * beta_3)/(mu_3^2)
Ra_1 = (Pr_3) * (Gr_1)
Nusselt_2 = (0.825 + ((0.387*Ra_1^(1/6))/((1+(0.492/Pr_3)^(9/16))^(8/27))))^2

h_2 = (Nusselt_2 * k_1) / d_2
R_3 = 1/(h_6 * A_o_1)                            {resistance due to convection}

Q_1 = (T_avg_1 - T_7) / (R_1 + R_2 + R_3)        {Heat provided by HEX to the salt water}
Q_1 * time_1 = (rho_6 * V_1) * Cp_3 * (T_5 - T_7)    {total heat (kJ) provided by the HTF, solves for
T_15}
=========================================================================}

"Heat Transfer in kJ *********************************************************************************************"

time_1 = L_1 / Vel_1                             {time that the HTF remains in the HEX}
Heat_1 = Q_1 * time_1                            {kJ transferred through HEX}

"DESIRED EVAPORATION OF WATER **************************************************************************"

Q_2 = m_dot_2 * ((Cp_2 * ( T_6 - T_7)) + (dh_1))     {Q required to evaporate desired m_dot_2}

"ENERGY LOSSES -- CHOOSE FORCED OR NATURAL CONVECTION ***********************************"

"Conductive Resistance"

R_4 = ln((d_5/2)/(d_4/2)) / (k_5 * 2 * pi * ht_3)    {conduction resistance through boiler}

"Convective Resistance"

    "IF forced convection"

Re_2 = (rho_3 * Vel_2 * d_5) / mu_2              {Reynolds number of air over troughs}
Nusselt_3 = C * Re_2^m * Pr_2^(1/3)              {Nusselt number of air over troughs}
    C = 0.683                                    {for 40<Re<40000}
    m = 0.466                                    {for 40<Re<40000}

{=========================================================================
```

```
"IF natural convection"
DT_1 = T_6 - T_1                              {temperature difference between saturation and
air}
Gr_2 = (d_5^3 * rho_3^2 * g * DT_1* beta_1)/(mu_2^2)
Ra_2 = (Pr_2) * (Gr_2)
Nusselt_3 = (0.825 + ((0.387*Ra_2^(1/6))/((1+(0.492/Pr_2)^(9/16))^(8/27))))^2
=============================================================================}

h_3 = Nusselt_3 * k_4 /d_5                    {heat transfer coefficient for convection between
air and boiler}
R_5 = 1/(h_3 * A_o_2)                         {resistance to natural convection through boiler}

"Heat Loss"
Q_3 = (T_6 - T_1) / (R_4 + R_5)               {losses from boiler}


"*******************************************************************************************************************
PARABOLIC TROUGH
*******************************************************************************************************************"

"SUBSYSTEM PARAMETERS ********************************************************************************"

"Solar Collector Pipe"

DT_2 = T_3 - T_2
epsilon_1 = 1                                 {emissivity}
Q_9 = m_dot_1 * Cp_1 * (T_3-T_2)              {solves for T_3, exit trough temp}
refl_1 = 0.85                                 {reflectivity of mirror}
T_2 =98.2 {C} + 273                           {temp of HTF entering trough}
trans_1 = 0.86                                {transmitivity of protective envelope}
Vel_3 = V_dot_3 / A_c_2                       {velocity of HTF through troughs}

"GEOMETRIES ********************************************************************************************"

"Trough"
L_3 = 18 {in} * 0.0254                        {chord/width}
L_4 = 32 {ft} * 0.3048                        {total length of trough}

"Pipe"
A_c_2 = pi/4 * d_7^2                          {cross sectional area of HCE}
A_i_3 = pi * d_7 * L_4                        {inner surface area of HCE}
d_6 = 1.24 {in} * 0.0254                      {OD of pipe}
d_7 = d_6 - (2*L_2)                           {ID of pipe}
L_2 = 0.042 {in} * 0.0254                     {thickness of pipe, other options are 0.042,
0.049, 0.06, and 0.072 "}

"CONVECTIVE HEAT TRANSFER TO SURROUNDINGS -- CHOOSE FORCED OR NATURAL
CONVECTION ****************"

    "IF forced convection"
{=============================================================================
Re_3 = (rho_3 * Vel_2 * d_6) / mu_2           {Reynolds number of air over troughs}
Nusselt_4 = C * Re_3^m * Pr_2^(1/3)           {Nusselt number of air over troughs}
    {
```

```
   C = 0.683                                      {for 40<Re<40000    C and m values previously
defined from boiler, check Re_3}
   m = 0.466                                      {for 40<Re<40000}
   }
h_4 = Nusselt_4 * k_4 /d_6
==================================================================================}

   "IF natural convection"
DT_3 = T_avg_2 - T_1                              {temp difference between HTF and
surroundings}
Gr_3 = (d_6^3 * rho_3^2 * g * DT_3* beta_1)/(mu_2^2)
Ra_3 = (Pr_2) * (Gr_3)
Nusselt_4 = (0.825 + ((0.387*Ra_3^(1/6))/((1+(0.492/Pr_2)^(9/16))^(8/27))))^2
h_4 = Nusselt_4 * k_4 /d_6

"ENERGY BALANCE ****************************************************************************************"
Q_11 = q_flux_2 * L_3 * L_4                       {energy in from sun, solve for L_4}
Q_7 = (T_avg_2^4 - T_1^4) * epsilon_1 * sigma_1 * d_6 * pi * L_4    {energy loss to radiation}
Q_8 = h_4 * pi * d_6 * L_4 * (T_2 - T_1)          {energy loss due to convection to surroundings}

Q_9= (refl_1 * trans_1 * Q_11) - Q_7 - Q_8        {Net Q into trough}

time_2 = L_4 / (v_dot_3/A_c_2)                    {time of HTF in troughs}
Heat_9 = Q_9 * time_2                             {kJ absorbed by HTF in troughs}

"TO CALCULATE DESIRED Q_10, M_DOT_1, OR DT_2 ****************************************************"

Q_10 = m_dot_1 * Cp_1 * DT_2                      {Q required to obtain specified DT_2 based on
m_dot_1}


"TROUGH EFFICIENCY *************************************************************************************"
eta_trough = Q_9 / Q_11                           {efficiency of trough}
```

D.2 Condenser Length

```
"*****************************************************************************************************
CONDENSER LENGTH
*****************************************************************************************************"

"SYSTEM PROPERTIES*************************************************************************************"
g = 9.81 [m/s^2]
k_2 = 400 * 10^(-3)                          {conductivity of copper [kW/(m*K)]}
P_1 = 100 [kPa]

"CONDENSING FLUID -- CHOOSE WATER OR AIR***************************************************************"
T_11 = 80 {C} + 273                          {condensing fluid temperature}

{===========================================================================
   "Water"
beta_3 = 624.2 * 10^(-6)                     {coeff of thermal expansion of condensing fluid}
k_6 = 668 * 10^(-3)                          {thermal conductivity of condensing fluid}
mu_4 = viscosity(water, P=P_1,T=T_11)        {dynamic viscosity of condensing fluid}
Pr_5 = 2.29                                  {prandtl number of condensing fluid}
rho_5 = density(water, P=P_1, T=T_11)        {density of condensing fluid}
===========================================================================}

   "Air"
beta_3 = 1/T_11                              {coeff of thermal expansion of condensing fluid}
k_6 = 0.024 * 10^(-3)                        {thermal conductivity of condensing fluid}
nu_2 = 20.92*10^(-6)                         {kinematic viscosity of condensing fluid}
mu_4 = nu_2 * rho_5                          {dynamic viscosity of condensing fluid}
Pr_5 = prandtl(air,T=T_11)                   {prandtl number of condensing fluid}
rho_5 = density(air, P=P_1, T=T_11)          {density of condensing fluid}


"WATER AND VAPOR **************************************************************************************"
Cp_2 = specheat(water, P=P_1, x=0)           {specific heat of liquid water}
dh_1 = he_2 - he_1                           {enthalpy difference due to latent heat}
dh_2 = he_1 - he_3                           {enthalpy difference due to sensible heat}
he_1 = enthalpy(water, P=P_1, x=0)           {enthalpy of water right after condensing (x=0)}
he_2 = enthalpy(water, P=P_1, x=1)           {enthalpy of steam entering condenser}
he_3 = enthalpy(water, P=P_1, T = T_9)       {enthalpy of water exiting condenser, into clean
tank}
m_dot_2 = V_dot_1 * rho_1                    {desired mass flow rate of vapor kg/s}
mu_3 = viscosity(water, P=P_1, x=0)          {dynamic viscosity of water}
rho_1 = density(water, P=P_1, x=1)           {density of vapor}
rho_4 = density(water, P=P_1, x=0)           {density of condensed water, at x=0}
T_9 = 95 {C} + 273                           {temperature of vapor exiting condenser}
T_avg_3 = (T_6 + T_9) / 2                    {average temperature of water in condenser}
T_6 = temperature(water, P=P_1, x=1)         {saturation temperature}
V_dot_1 = V_dot_2 / 951019                   {volumetric flow rate, m^3/s}
V_dot_2 = 1 [gal/hr]

"GEOMETRIES********************************************************************************************"

"Condenser"
d_8 = (3/8) {in} * 0.0254                    {OD of condenser}
d_9 = 0.311 {in} * 0.0254                    {ID of condenser}
```

```
A_i_2 = L_5 * pi * d_9                                    {inner surface area of condenser}
A_o_3 = L_5 * pi * d_8                                    {outer surface area of condenser}


"ENERGY BALANCE ************************************************************************************************"

Q_4 = dh_1 * m_dot_2                                      {latent heat to be removed by condenser, kW}
Q_5= dh_2 * m_dot_2                                       {sensible heat to be removed by condenser, kW}

Q_6 = Q_4 + Q_5                                           {total heat to be removed by condenser}

 Q_6 = (T_avg_3 - T_11) / ({R_6 +} R_7 + R_8)
Q_6= (T_avg_3 - T_10) / ({R_6 +} R_7)

"RESISTANCES
**********************************************************************************************************************"

"Film condensation on inner tube to surface ***********************************************************************"

dh_3 = dh_1+ (3/8) * Cp_2 * ( T_avg_3 - T_10)             {modified latent heat, pg 654 HT book}

h_6 = 0.555 * ( (g * rho_4* (rho_4 - rho_1) * k_6^3 * dh_3) / (mu_3 * (T_avg_3 - T_10) * d_9))^0.25

R_6 = 1/(h_6 * A_i_2)

"Conduction of condenser ***************************************************************************************"

R_7 = ln((d_8/2) / (d_9/2)) / (2 * pi * k_2 * L_5)

"Natural convection from condenser to condensing fluid ***********************************************************"
Gr_4 = (d_8^3 * rho_5^2 * g * (T_10 - T_11)* beta_3)/(mu_4^2)
Ra_4 = (Pr_5) * (Gr_4)
Nusselt_5 = (0.825 + ((0.387 * Ra_4^(1/6))/((1+(0.492/Pr_5)^(9/16))^(8/27))))^2
h_5 = Nusselt_5 * k_6 /d_8

R_8 = 1/(h_5 * A_o_3)
```

D.3 EES Nomenclature

Variable	Units	Description
A_c_1	m^2	Cross sectional area of HEX pipe
A_c_2	m^2	Cross sectional area of HCE
A_i_1	m^2	Inner surface area of the HEX
A_i_2	m^2	Inner surface area of HCE
A_i_3	m^2	Inner surface area of condenser
A_o_1	m^2	Outer surface area of HEX
A_o_2	m^2	Outer surface area of boiler
A_o_3	m^2	Outer surface area of condenser
beta_1	1/K	Coefficient of thermal expansion for air
beta_2	1/K	Coefficient of thermal expansion for water
beta_3	1/K	Coefficient of thermal expansion for condensing fluid
C_s_f		Constant for nucleate boiling heat flux, given in HT textbook pg 628
Cp_1	kJ/kgK	Specific heat of HTF
Cp_2	kJ/kgK	Specific heat of liquid water
c_1	m	Circumference of one loop of the helical HEX
d_1	m	Inner diameter of HEX tubing
d_2	m	Outer diameter of HEX tubing
d_3	m	Center to center diameter of one loop of the HEX helix
d_4	m	Inner diameter of the boiler
d_5	m	Outer diameter of boiler
d_6	m	Outer diameter of pipe for HTF
d_7	m	Inner diameter of pipe for HTF
d_8	m	Outer diameter of condenser pipe
d_9	m	Inner diameter of condenser
dh_1	kJ/kg	Latent heat of vaporization of water
dh_2	kJ/kg	Sensible enthalpy loss of vapor in condenser
dh_3	kJ/kg	Modified latent heat (pg 654, HT book) for film condensation resistance
DT_1	K	Temp difference between saturation and air
DT_2	K	Temp difference between HTF in and out of trough
DT_3	K	Temp difference between HTF and surroundings
$epilson_1$		Emissivity of pipe in collector
eta_trough		Efficiency of trough
g	m/s^2	Acceleration due to gravity
Gr_1		Grashof number for natural convection from HEX to salt water in boiler
Gr_2		Grashof number for convection from air outside boiler
Gr_3		Grashof number for natural convection from pipe to surroundings
Gr_4		Grashof number for condensing fluid
h_1	kW/m^2K	Heat transfer coefficient for convection from flow of HTF in HEX
H_2	kW/m^2K	Heat transfer coefficient for natural convection on HEX to sw in boiler
H_3	kW/m^2K	Heat transfer coefficient for natural convective air on outer surface of boiler
H_4	kW/m^2K	Heat transfer coefficient for natural convection to air outside collector pipe
H_5	kW/m^2K	Heat transfer coefficient for natural convection of condensing fluid
H_6	kW/m^2K	Heat transfer coefficient for film condensation
he_1	kJ/kg	Enthalpy of water at P=P_1, x=0
he_2	kJ/kg	Enthalpy of water at P=P_1, x=1
he_3	kJ/kg	Enthalpy of water at T_9
Heat_1	kJ	Total energy transferred through HEX
Heat_2	kJ	Total energy absorbed by HTF through trough
ht_1	m	Height of one loop of HEX helix
ht_2	m	Height of salt water in boiler

ht_3	m	Height of boiler
k_1	kW/mK	Thermal conductivity of water at 70 C
k_2	kW/mK	Thermal conductivity of copper
k_3	kW/mK	Thermal conductivity of HTF
k_4	kW/mK	Thermal conductivity of air
k_5	kW/mK	Thermal conductivity of boiler material
k_6	kW/mK	Thermal conductivity of condensing fluid
L_1	m	Total length of the HEX
L_2	m	Thickness of trough pipe
L_3	m	Length of chord across parabolic trough
L_4	m	Total length of trough collectors
L_5	m	Total length of condenser
m_1	kg	Mass of sw in boiler
$m_{dot,1}$	kg/s	Mass flow rate of HTF
$m_{dot,2}$	kg/s	Mass flow rate of vapor
mu_1	kg/ms	Dynamic viscosity of HTF at P=P_1, T=T_11
mu_2	kg/ms	Dynamic viscosity of air at T=T_1
mu_3	kg/ms	Dynamic viscosity of water at P=P_1, x=0
mu_4	kg/ms	Dynamic viscosity of condensing fluid at T=T_11
n_1		Number of loops in HEX helix
nu_1	m^2/s	Kinematic viscosity of HTF
nu_2	m^2/s	Kinematic viscosity of condensing air
Nusselt_1		Nusselt number of HTF through HEX
Nusselt_2		Nusselt number for natural convection from HEX to salt water in boiler
Nusselt_3		Nusselt number for natural convection of air on outer surface of boiler
Nusselt_4		Nusselt number for convection from collector pipe to surroundings
Nusselt_5		Nusselt number of condensing fluid for natural convection over condenser
P_1	kPa	Pressure in boiler
Pr_1		Prandtl number of HTF
Pr_2		Prandtl number of atmospheric air at T_1
Pr_3		Prandtl number of water
Pr_4		Prandtl number of condensing fluid
Q_1	kW	Heat transfer from HTF to surface of HEX
Q_2	kW	Q required to evaporate m_dot_2
Q_3	kW	Q loss through boiler
Q_4	kW	Q required to condense vapor (latent)
Q_5	kW	Q required to change temperature after vapor condensed (sensible)
Q_6	kW	Total Q transfer required in condenser
Q_7	kW	Q lost to radiation
Q_8	kW	Q lost to convection
Q_9	kW	Net heat transferred to HTF through trough
Q_{10}	kW	Q required to obtain specified DT_2 based on m_dot_1
Q_{11}	kW	Q into the trough (from sun)
$q\_flux\__1$	kW/m^2	Heat flux for nucleate boiling in boiler.
$q\_flux\__2$	kW/m^2	Heat flux from sun
R_1	K/kW	Resistance to convective heat transfer from HTF to HEX inner surface
R_2	K/kW	Resistance to conductive heat transfer through helical HEX
R_3	K/kW	Resistance due to natural convection on HEX outer surface
R_4	K/kW	Resistance to conduction through boiler
R_5	K/kW	Resistance due to natural convection on boiler outer surface
R_6	K/kW	Resistance due to film condensation
R_7	K/kW	Resistance due to conduction through condenser
R_8	K/kW	Resistance due to natural convective to condensing fluid

Ra_1		Rayleigh number (D) natural convection to salt water in boiler
Ra_2		Rayleigh number (D) natural convection to outer surface of boiler
Ra_3		Rayleigh number (D) natural convection to outer surface of collector pipe
Ra_4		Rayleigh number (D) of condensing fluid
Re_1		Reynolds number (D) of HTF
Re_2		Reynolds number of air over boiler
Re_3		Reynolds number of air over troughs
Refl_1		Reflectivity of trough
rho_1	kg/m^3	Density of vapor at P=P_1, x=1
rho_2	kg/m^3	Density of HTF
rho_3	kg/m^3	Density of air at T_1
rho_4	kg/m^3	Density of compressed liquid water at P=P_1, T=T_9
rho_5	kg/m^3	Density of condensing fluid at P=P_1, T=T_11
rho_6	kg/m^3	Density of liquid water in boiler
$sigma_1$	kW/m^2K^4	Stefan-Boltzmann constant
spv_1	m^3/kg	Specific volume of HTF
$T_{avg,1}$	K	Average temperature of HTF in boiler
$T_{avg,2}$	K	Avg temp of HTF in troughs
$T_{avg,3}$	K	Average temp of condensing vapor
T_1	K	Atmospheric temperature
T_2	K	HTF Temperature into the solar collector
T_3	K	HTF Temp out of the solar collector
T_4	K	Temperature out of boiler
T_5	K	Temperature of sw in boiler after heating
T_6	K	Saturation temperature of water at $P=P_1$, x=1
T_7	K	Temp of salt water in the boiler
T_8	K	Temp of HEX surface
T_9	K	Temperature of condensed liquid exiting condenser
T_{10}	K	Condenser outer surface temperature
T_{11}	K	Temperature of fluid surrounding condenser
$Time_1$		Time of HTF in HEX
Time_2		Time of HTF in troughs
Trans1		Transmitivity of protective envelope
V_1	m^3	Volume of salt water in boiler
$V_{dot,1}$	m^3/s	Volumetric flow rate of vapor
$V_{dot,2}$	gal/hr	Volumetric flow rate of vapor
$V_{dot,3}$	m^3/s	Volumetric flow rate of HTF
$V_{dot,4}$	gal/hr	Volumetric flow rate of HTF
Vel_1	m/s	Velocity of HTF in HEX
Vel_2	m/s	Velocity of ambient air
Vel_3	m/s	Velocity of HTF in troughs

Appendix E: Data Sheets

E.1 K-Thermocouple

19-2235; Rev 1; 3/02

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

MAX6675

General Description

The MAX6675 performs cold-junction compensation and digitizes the signal from a type-K thermocouple. The data is output in a 12-bit resolution, SPI™-compatible, read-only format.

This converter resolves temperatures to 0.25°C, allows readings as high as +1024°C, and exhibits thermocouple accuracy of 8LSBs for temperatures ranging from 0°C to +700°C.

The MAX6675 is available in a small, 8-pin SO package.

Applications

Industrial

Appliances

HVAC

Automotive

SPI is a trademark of Motorola, Inc.

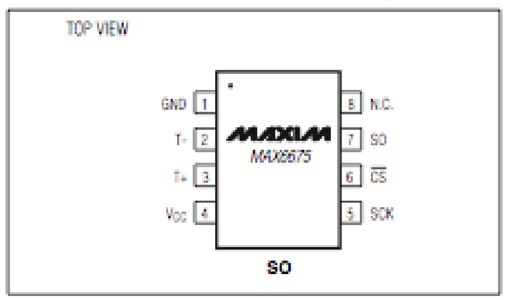
Features

- Direct Digital Conversion of Type -K Thermocouple Output
- Cold-Junction Compensation
- Simple SPI-Compatible Serial Interface
- 12-Bit, 0.25°C Resolution
- Open Thermocouple Detection

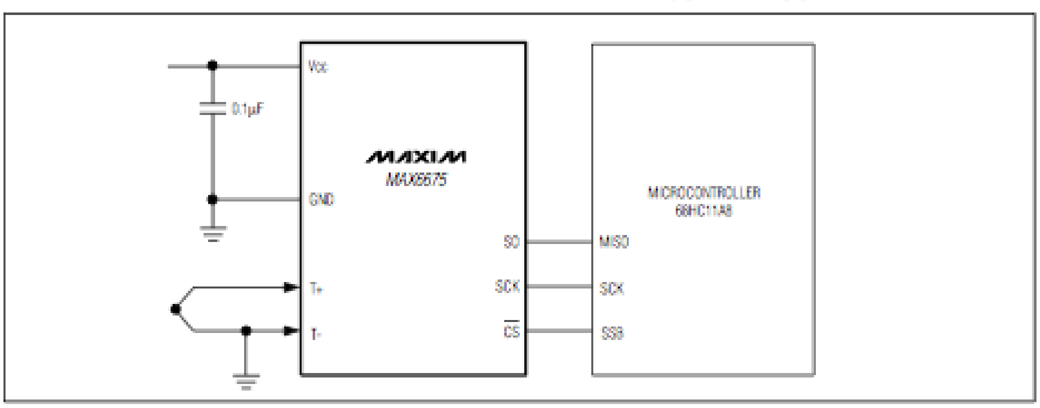
Ordering Information

PART	TEMP RANGE	PIN-PACKAGE
MAX6675ISA	-20°C to +85°C	8 SO

Pin Configuration



Typical Application Circuit



Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

ABSOLUTE MAXIMUM RATINGS

Supply Voltage (V_{CC} to GND) .... -0.3V to +6V
SO, SCK, $\overline{CS}$, T-, T+ to GND ....-0.3V to V_{CC} + 0.3V
SO Current 50mA
ESD Protection (Human Body Model) .... ±2000V
Continuous Power Dissipation (T_A = +70°C)
8-Pin SO (derate 5.88mW/°C above +70°C) 471mW
Operating Temperature Range ....-20°C to +85°C
Storage Temperature Range ....-65°C to +150°C
Junction Temperature .... +150°C
SO Package
Vapor Phase (60s) . ...+215°C
Infrared (15s) ....+220°C
Lead Temperature (soldering, 10s) .... +300°C

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS

(V_{CC} = +3.0V to +5.5V, T_A = -20°C to +85°C, unless otherwise noted. Typical values specified at +25°C.) (Note 1)

PARAMETER	SYMBOL	CONDITIONS		MIN	TYP	MAX	UNITS
Temperature Error		$T_{THERMOCOUPLE}$ = +700°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-5		+5	LSB
			V_{CC} = +5V	-6		+6	
		$T_{THERMOCOUPLE}$ = 0°C to +700°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-8		+8	
			V_{CC} = +5V	-9		+9	
		$T_{THERMOCOUPLE}$ = +700°C to +1000°C, T_A = +25°C (Note 2)	V_{CC} = +3.3V	-17		+17	
			V_{CC} = +5V	-19		+19	
Thermocouple Conversion Constant					10.25		µV/LSB
Cold-Junction Compensation Error		T_A = -20°C to +85°C (Note 2)	V_{CC} = +3.3V	-3.0		+3.0	°C
			V_{CC} = +5V	-3.0		+3.0	
Resolution					0.25		°C
Thermocouple Input Impedance					60		kΩ
Supply Voltage	V_{CC}			3.0		5.5	V
Supply Current	I_{CC}				0.7	1.5	mA
Power-On Reset Threshold		V_{CC} rising		1	2	2.5	V
Power-On Reset Hysteresis					50		mV
Conversion Time		(Note 2)			0.17	0.22	s
SERIAL INTERFACE							
Input Low Voltage	V_{IL}					0.3 x V_{CC}	V
Input High Voltage	V_{IH}			0.7 x V_{CC}			V
Input Leakage Current	I_{LEAK}	V_{IN} = GND or V_{CC}				±5	µA
Input Capacitance	C_{IN}				5		pF

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

ELECTRICAL CHARACTERISTICS (continued)

(V_{CC} = +3.0V to +5.5V, T_A = -20°C to +85°C, unless otherwise noted. Typical values specified at +25°C.) (Note 1)

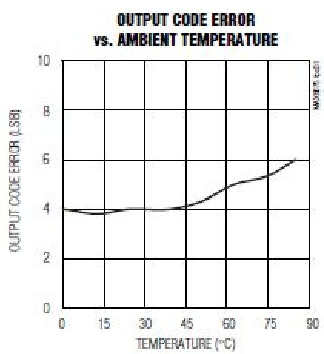
PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Output High Voltage	V_{OH}	I_{SOURCE} = 1.6mA	V_{CC} - 0.4			V
Output Low Voltage	V_{OL}	I_{SINK} = 1.6mA			0.4	V
TIMING						
Serial Clock Frequency	f_{SCL}				4.3	MHz
SCK Pulse High Width	t_{CH}		100			ns
SCK Pulse Low Width	t_{CL}		100			ns
CSB Fall to SCK Rise	t_{CSS}	C_L = 10pF	100			ns
CSB Fall to Output Enable	t_{DV}	C_L = 10pF			100	ns
CSB Rise to Output Disable	t_{TR}	C_L = 10pF			100	ns
SCK Fall to Output Data Valid	t_{DO}	C_L = 10pF			100	ns

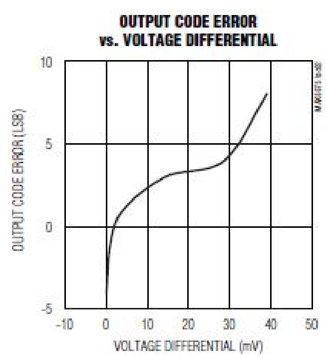
Note 1: All specifications are 100% tested at T_A = +25°C. Specification limits over temperature (T_A = T_{MIN} to T_{MAX}) are guaranteed by design and characterization, not production tested.

Note 2: Guaranteed by design. Not production tested.

Typical Operating Characteristics

(V_{CC} = +3.3V, T_A = +25°C, unless otherwise noted.)





Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

Pin Description

PIN	NAME	FUNCTION
1	GND	Ground
2	T-	Alumel Lead of Type-K Thermocouple. Should be connected to ground externally.
3	T+	Chromel Lead of Type-K Thermocouple
4	V_{CC}	Positive Supply. Bypass with a 0.1µF capacitor to GND.
5	SCK	Serial Clock Input
6	$\overline{CS}$	Chip Select. Set $\overline{CS}$ low to enable the serial interface.
7	SO	Serial Data Output
8	N.C.	No Connection

Detailed Description

The MAX6675 is a sophisticated thermocouple-to-digital converter with a built-in 12-bit analog-to-digital converter (ADC). The MAX6675 also contains cold-junction compensation sensing and correction, a digital controller, an SPI-compatible interface, and associated control logic.

The MAX6675 is designed to work in conjunction with an external microcontroller (µC) or other intelligence in thermostatic, process-control, or monitoring applications.

Temperature Conversion

The MAX6675 includes signal-conditioning hardware to convert the thermocouple's signal into a voltage compatible with the input channels of the ADC. The T+ and T- inputs connect to internal circuitry that reduces the introduction of noise errors from the thermocouple wires.

Before converting the thermoelectric voltages into equivalent temperature values, it is necessary to compensate for the difference between the thermocouple cold-junction side (MAX6675 ambient temperature) and a 0°C virtual reference. For a type-K thermocouple, the voltage changes by 41µV/°C, which approximates the thermocouple characteristic with the following linear equation:

$$V_{OUT} = (41\mu V / {}^{\circ}C) \times (T_R - T_{AMB})$$

Where:

V_{OUT} is the thermocouple output voltage (µV).

T_R is the temperature of the remote thermocouple junction (°C).

T_{AMB} is the ambient temperature (°C).

Cold-Junction Compensation

The function of the thermocouple is to sense a difference in temperature between two ends of the thermocouple wires. The thermocouple's hot junction can be read from 0°C to +1023.75°C. The cold end (ambient temperature of the board on which the MAX6675 is mounted) can only range from -20°C to +85°C. While the temperature at the cold end fluctuates, the MAX6675 continues to accurately sense the temperature difference at the opposite end.

The MAX6675 senses and corrects for the changes in the ambient temperature with cold-junction compensation. The device converts the ambient temperature reading into a voltage using a temperature-sensing diode. To make the actual thermocouple temperature measurement, the MAX6675 measures the voltage from the thermocouple's output and from the sensing diode. The device's internal circuitry passes the diode's voltage (sensing ambient temperature) and thermocouple voltage (sensing remote temperature minus ambient temperature) to the conversion function stored in the ADC to calculate the thermocouple's hot-junction temperature.

Optimal performance from the MAX6675 is achieved when the thermocouple cold junction and the MAX6675 are at the same temperature. Avoid placing heat-generating devices or components near the MAX6675 because this may produce cold-junction-related errors.

Digitization

The ADC adds the cold-junction diode measurement with the amplified thermocouple voltage and reads out the 12-bit result onto the SO pin. A sequence of all zeros means the thermocouple reading is 0°C. A sequence of all ones means the thermocouple reading is +1023.75°C.

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

Applications Information

Serial Interface

The *Typical Application Circuit* shows the MAX6675 interfaced with a microcontroller. In this example, the MAX6675 processes the reading from the thermocouple and transmits the data through a serial interface. Force $\overline{CS}$ low and apply a clock signal at SCK to read the results at SO. Forcing $\overline{CS}$ low immediately stops any conversion process. Initiate a new conversion process by forcing $\overline{CS}$ high.

Force $\overline{CS}$ low to output the first bit on the SO pin. A complete serial interface read requires 16 clock cycles. Read the 16 output bits on the falling edge of the clock. The first bit, D15, is a dummy sign bit and is always zero. Bits D14–D3 contain the converted temperature in the order of MSB to LSB. Bit D2 is normally low and goes high when the thermocouple input is open. D1 is low to provide a device ID for the MAX6675 and bit D0 is three-state.

Figure 1a is the serial interface protocol and Figure 1b shows the serial interface timing. Figure 2 is the SO output.

Open Thermocouple

Bit D2 is normally low and goes high if the thermocouple input is open. In order to allow the operation of the open thermocouple detector, T- must be grounded. Make the ground connection as close to the GND pin as possible.

Noise Considerations

The accuracy of the MAX6675 is susceptible to power-supply coupled noise. The effects of power-supply noise can be minimized by placing a 0.1µF ceramic bypass capacitor close to the supply pin of the device.

Thermal Considerations

Self-heating degrades the temperature measurement accuracy of the MAX6675 in some applications. The magnitude of the temperature errors depends on the thermal conductivity of the MAX6675 package, the mounting technique, and the effects of airflow. Use a large ground plane to improve the temperature measurement accuracy of the MAX6675.

The accuracy of a thermocouple system can also be improved by following these precautions:

- Use the largest wire possible that does not shunt heat away from the measurement area.
- If small wire is required, use it only in the region of the measurement and use extension wire for the region with no temperature gradient.
- Avoid mechanical stress and vibration, which could strain the wires.
- When using long thermocouple wires, use a twisted-pair extension wire.
- Avoid steep temperature gradients.
- Try to use the thermocouple wire well within its temperature rating.
- Use the proper sheathing material in hostile environments to protect the thermocouple wire.
- Use extension wire only at low temperatures and only in regions of small gradients.
- Keep an event log and a continuous record of thermocouple resistance.

Reducing Effects of Pick-Up Noise

The input amplifier (A1) is a low-noise amplifier designed to enable high-precision input sensing. Keep the thermocouple and connecting wires away from electrical noise sources.

Chip Information

TRANSISTOR COUNT: 6720

PROCESS: BiCMOS

Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

MAX6675

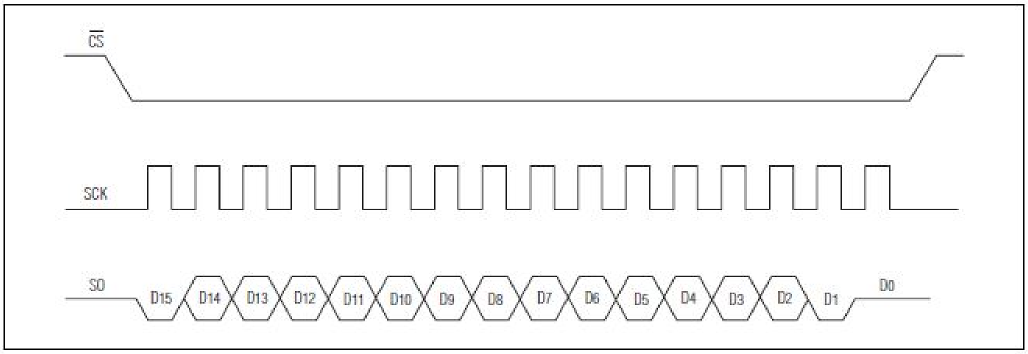


Figure 1a. Serial Interface Protocol

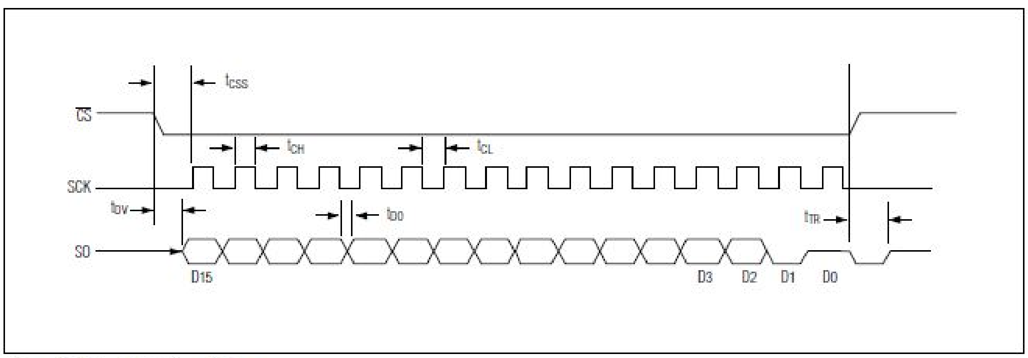


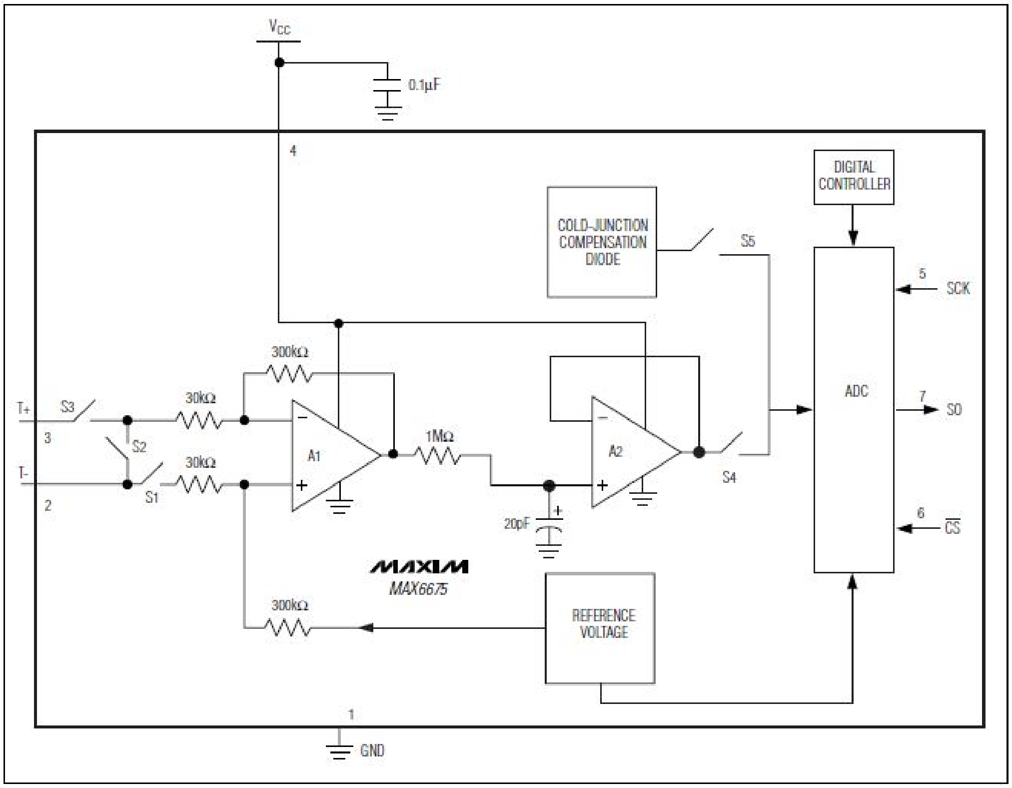
Figure 1b. Serial Interface Timing

BIT	DUMMY SIGN BIT	12-BIT TEMPERATURE READING												THERMOCOUPLE INPUT	DEVICE ID	STATE
Bit	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	0	MSB											LSB		0	Three-state

Figure 2. SO Output

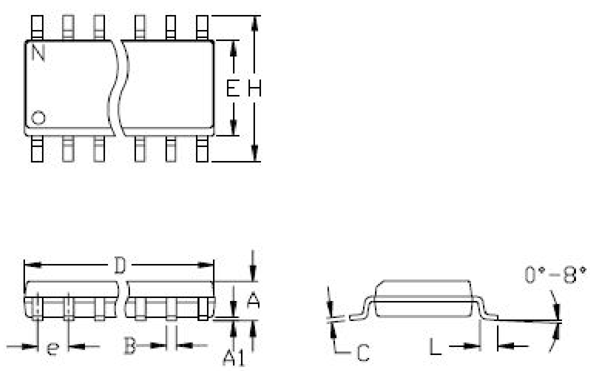
Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

Block Diagram



Cold-Junction-Compensated K-Thermocouple-to-Digital Converter (0°C to +1024°C)

Package Information



	INCHES		MILLIMETERS	
	MIN	MAX	MIN	MAX
A	0.053	0.069	1.35	1.75
A1	0.004	0.010	0.10	0.25
B	0.014	0.019	0.35	0.49
C	0.007	0.010	0.19	0.25
e	0.050		1.27	
E	0.150	0.157	3.80	4.00
H	0.228	0.244	5.80	6.20
h	0.010	0.020	0.25	0.50
L	0.016	0.050	0.40	1.27

	INCHES		MILLIMETERS			
	MIN	MAX	MIN	MAX	N	MS012
D	0.189	0.197	4.80	5.00	8	A
D	0.337	0.344	8.55	8.75	14	B
D	0.386	0.394	9.80	10.00	16	C

NOTES:
1. D&E DO NOT INCLUDE MOLD FLASH
2. MOLD FLASH OR PROTRUSIONS NOT TO EXCEED .15mm (.006")
3. LEADS TO BE COPLANAR WITHIN .102mm (.004")
4. CONTROLLING DIMENSION: MILLIMETER
5. MEETS JEDEC MS012-XX AS SHOWN IN ABOVE TABLE
6. N = NUMBER OF PINS

MAXIM — 120 SAN GABRIEL DR. SUNNYVALE CA 94086 FAX (408) 737 7194 — PROPRIETARY INFORMATION | TITLE: PACKAGE FAMILY OUTLINE: SOIC .150" | 1/1 | DOCUMENT CONTROL NUMBER: 21-0041 | REV: A

Maxim cannot assume responsibility for use of any circuitry other than circuitry entirely embodied in a Maxim product. No circuit patent licenses are implied. Maxim reserves the right to change the circuitry and specifications without notice at any time.

E.2 Motor Speed Controller

UK1130
VERSION 1.0

30A Digital DC PWM Motor Speed Controller

Control the speed of a DC motor without sacrificing torque. This Pulse-Width-Modulation (PWM) DC motor speed controller can provide up to a maximum continuous current of 30A to your DC motor or other DC load thanks to a digital microcontroller based (PIC) design and two highly efficient High-Power 110A MOSFETs for cooler operation.

The controller has two modes of operation: **Fixed** or **Variable** frequency. The fixed frequency mode of operation runs the controller at 100 Hz. In the variable frequency mode of operation, the frequency is adjustable from 244 Hz to 3.125 KHz. Duty cycle is fully adjustable from 0% to 100% in both modes.

The controller also offers built-in **soft-start** feature that greatly reduces the mechanical stress on the motor as well as the electrodynamic stress on the attached cables and battery therefore extending the life span of the whole system. When power is connected to the circuit, the duty cycle will start from 0% and go up to the preset value in about 1 to 1.5 seconds.

An optional fan is available separately (Model #: FAN-12V) and recommended for continuous operation at maximum power or for high frequency at high current applications.

Recommended Generic Case: BX-1591LF

Operating Instructions

1. The controller has two modes of operation: "Fixed" and "Variable" frequency. With the jumper head placed on "J1", the controller will be in the Fixed mode of operation. If removed, the controller will be in the Variable mode. Note that to change from one mode to another, you first have to disconnect the power supply.

VARIABLE FREQUENCY (244 Hz – 3.125 KHz)	FIXED FREQUENCY (100 Hz)
J1	**J1**

2. Connect the controller to the power supply (6 to 24V DC) and the load as indicated on the Wiring Diagram.
3. You can control the Duty Cycle using potentiometer "P2" and if in the variable frequency mode, the Frequency using potentiometer "P1".

www.canakit.com
Manufacturer of High Quality Electronic Kits & Modules

Manufactured by:
Cana Kit Corporation

#118 – 2455 Dollarton Highway
North Vancouver • BC • V7H 0A2 • Canada
Tel: (604) 298-3305 • Fax: (604) 298-3390
Email: info@canakit.com

Web Site: www.canakit.com

Important Notes

An appropriately rated fuse (rated a little higher than the maximum current you expect to draw) is required to ensure safe operation.

The controller is NOT reverse-polarity protected. Double check all connections before applying power and always turn off the power supply before making any wiring changes.

Do not connect the load's negative terminal to the power supply ground. The controller switches the load's negative terminal to the ground via the MOSFET.

If operating the controller at maximum current continuously, or at high frequency and high current, it is recommended to add an appropriate fan to cool the MOSFETs. Two terminals marked "F–" and "F+" are available on the board in order to connect a fan of appropriate voltage (same as your supply voltage).

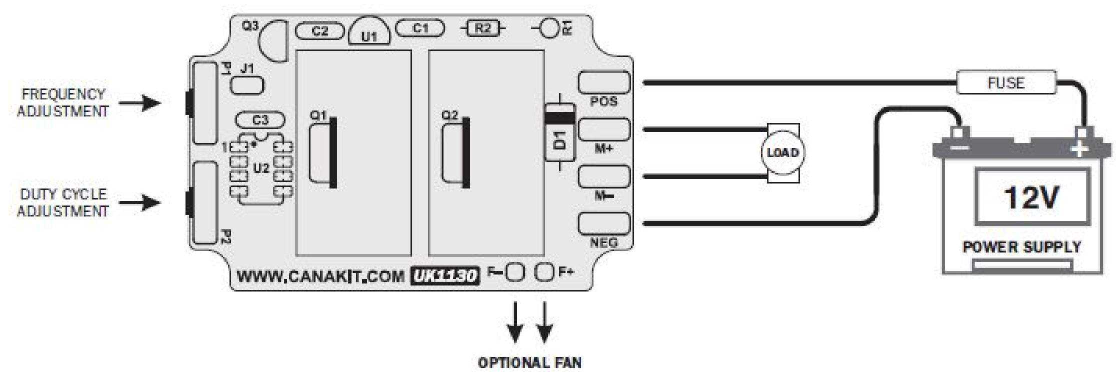
The MOSFETs heat sinks are electrically live and connected to the "M–" terminal. Make sure no wires touch the heat sinks.

Always use the shortest possible length for all wiring carrying high current to ensure minimal loss. The longer the wire, the higher the voltage drop across it which leads to a less efficient overall system.

Make sure all wires marked as "High Gauge" on the wiring diagram are of the appropriate AWG gauge depending on the maximum current you expect to draw.

Recommended AWG gauges are as follows:

AWG 14 : 15A
AWG 12 : 20A
AWG 10 : 30A



Cana Kit
www.canakit.com

Schematic Diagram

Manufactured by:
Cana Kit Corporation

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Tel: (604) 298-3305 • Fax: (604) 298-3390
Email: info@canakit.com

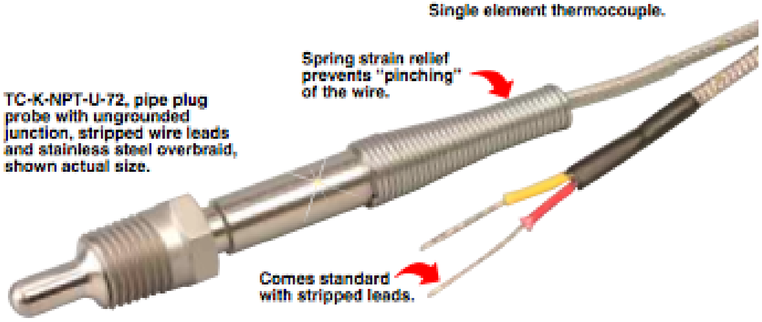
Web Site: www.canakit.com

E.3 Thermocouple Probe

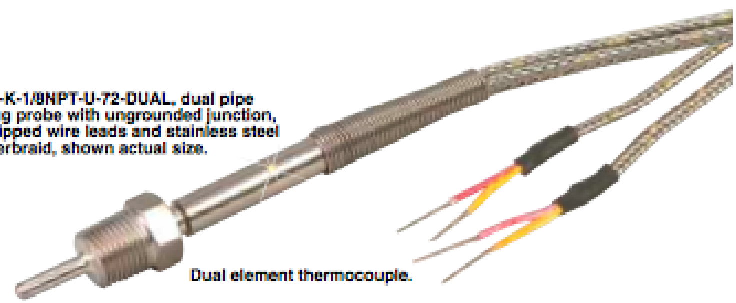
Rugged Pipe Plug Thermocouple Probe

TC-(*)-NPT Series

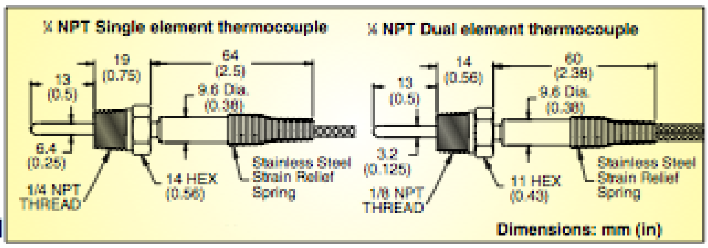
- Rugged 304 SS Design with Strain Relief Spring
- Single and Dual Elements
- ¼ or ⅛ NPT Mounting Thread
- 2 m (80") Stainless Steel Braid Over Fiberglass Lead Wire
- 20 AWG, Stranded for ¼ NPT 24 AWG, Stranded for ⅛ NPT Stainless Steel Overbraid–Resists Abrasions and Cuts, Yet Remains Flexible
- Withstands Pressures to 2500 psi at Ambient Temperatures
- Grounded and Ungrounded Junction Is Ideal For Vessel Application, Pressurized Chambers and Pipelines
- Exposed Junction Designed For Air Temperature Measurement and Monitoring of Gas Streams
- Stripped Leads Standard SMPW Connectors, Optional
- Choice J, K, T or E Thermocouple Types
- Grounded, Ungrounded or Exposed Junctions
- Special Custom Designs Having Different NPT Threads, Tip Diameters or Tip Lengths are Also Available
- Flush Tip Available, Consult Custom Engineering
- Probe Temperature Range to 650°C (1200°F)
- Transition Joint/Cable Temperature Range to 480°C (900°F)



TC-K-NPT-U-72, pipe plug probe with ungrounded junction, stripped wire leads and stainless steel overbraid, shown actual size.



TC-K-1/8NPT-U-72-DUAL, dual pipe plug probe with ungrounded junction, stripped wire leads and stainless steel overbraid, shown actual size.



To Order *Visit omega.com/tc-npt for Pricing and Details*

Mounting Thread	Model No.
¼	TC-(*)-NPT-(**)-72
	TC-(*)-1/4 NPT-(**)-72-DUAL
	TC-(*)-1/4 NPT-(**)-72-SMP
	TC-(*)-1/4 NPT-(**)-72-SMP-DUAL
⅛	TC-(*)-1/8 NPT-(**)-72
	TC-(*)-1/8 NPT-(**)-72-DUAL
	TC-(*)-1/8 NPT-(**)-72-SMP
	TC-(*)-1/8 NPT-(**)-72-SMP-DUAL

* *Specify calibration:* ***J, K, T*** *or* ***E.***
** *Specify junction type:* ***G*** *(Grounded),* ***E*** *(Exposed),* ***U*** *(Ungrounded).*
For lead wire length over 2 m (80"), use additional price per 300 mm (12") increments and modify model number.
Ordering Example: TC-K-NPT-G-72, *pipe plug style, Type K grounded junction thermocouple with ¼ NPT thread and 72" long extension leads.*

E.4 Duratherm-450

DURATHERM
EXTENDED LIFE FLUIDS

DURATHERM 450

OVERVIEW

Duratherm 450 is specifically engineered for applications requiring process heating and cooling efficiently between 30˚F and 450˚F.

Economical and thermally stable, Duratherm 450 heat transfer fluid offers an excellent alternative to costly synthetics and aromatic fluids while delivering precise and efficient cooling down to 30˚F.

APPLICATION

Duratherm 450 is specifically engineered for applications requiring process heating and cooling efficiently between 30°F and 450°F.

Economical and thermally stable, **Duratherm 450** offers an excellent alternative to costly synthetics and aromatic fluids while delivering precise and efficient cooling down to 30°F. **Duratherm 450** is an oxidative and thermally stable, high performance, long lasting, environmentally friendly heat transfer fluid. Offering precise temperature control and long life at an economical cost.

THE DIFFERENCE

Duratherm 450 heat transfer fluid contains the industries most effective and resilient blend of additives to ensure long-lasting, trouble-free service.

Our exclusive system includes a proprietary, dual stage anti-oxidant and a special blend of metal deactivators, extenders, and other agents that prolong fluid life and help keep systems clean. That also means longer life for parts like pumps and rotary seals.

LASTS LONGER

Oxidation can cripple your system. Left unchecked, it will ultimately cause catastrophic failure and costly downtime. That's why **Duratherm 450** heat transfer fluid offers unsurpassed levels of protection against oxidation, and a service life that other fluids simply can't match.

RUNS CLEANER

Duratherm 450 heat transfer fluid delivers superior resistance to sludging, a problem plaguing most other fluids. That makes it the best defense against extreme oxidation found in many of today's demanding manufacturing environments, including plastics processing, molding, casting, asphalt, paint, chemical and a wide variety of other applications.

In fact, our exclusive additive technology makes **Duratherm 450** heat transfer fluid the perfect solution for all applications, large or small requiring precise temperature control up to 450°F (232°C).

ENVIRONMENTAL

Duratherm 450 is environmentally friendly, non-toxic, non-hazardous and non-reportable. It poses no ill effect to worker safety and does not require special handling. After its long service life, **Duratherm 450** heat transfer fluid can easily be disposed of with other waste oils.

DURATHERM 450 PROPERTIES		
Appearance: colorless, clear and bright liquid		
Maximum Bulk/Use Temp.*	450°F	232°C
Flash Point ASTM D92	302°F	150°C
Fire Point ASTM D92	327°F	163°C
Autoignition ASTM E-659-78	625°F	329°C
Viscosity ASTM D445		
cSt at 104˚F / 40˚C	4.8	
cSt at 250°F / 121°C	1.3	
cSt at 450°F / 232°C	0.6	
Pour Point ASTM D97	-49°F	-45°C
Density ASTM D1298	**lb/ft3**	**g/ml**
at 100˚F / 38˚C	53.1	0.850
at 250°F / 121°C	49.5	0.793
at 450°F / 232°C	44.8	0.717
Average Molecular Weight	372	
Carbon Residue ASTM D189	0.005	% Mass
Sulphur Content X-RAY	<.001	weight %
CU Strip Corrosion ASTM D130	1a	
Thermal Expansion Coefficient	0.0564 %/˚F	0.1011 %/˚C
Thermal Conductivity	**BTU/hr F ft**	**W/m.K**
at 100˚F / 38˚C	0.082	0.142
at 500˚F / 260˚C	0.079	0.137
at 600˚F / 316˚C	0.074	0.128
Heat Capacity	**BTU/lb F**	**kJ/kg K**
at 100˚F / 38˚C	0.510	2.135
at 250°F / 121°C	0.57	2.386
at 450°F / 232°C	0.650	2.721
Vapor Pressure ASTM D2879	**psia**	**kPa**
at 100˚F / 38˚C	0.09	0.62
at 250°F / 121°C	0.33	2.28
at 450°F / 232°C	3.23	22.27
Distillation Range ASTM D2887	10%	481°F (249°C)
	90%	851°F (455°C)
***Maximum Film Temp.**	490°F	254°C

The values quoted are typical of normal production. They do not constitute a specification.

1-800-446-4910 www.heat-transfer-fluid.com

DURATHERM
EXTENDED LIFE FLUIDS

TECHNOLOGY

THE TECHNOLOGY BEHIND DURATHERM

Just about any fluid will transfer heat with some degree of efficiency; it's how long it lasts and how clean it keeps your system while its running that makes the difference.

We start with various highly stable, naturally resilient base stocks like highly refined, severely hydro treated pure paraffinic oils but where a lot of fluids stop there we continue with a proprietary blend of additives specific to heat transfer applications. These aren't just off the shelf generic additives; our package is finely tuned and formulated for heat transfer fluids.

While some might say the use of additives are not necessary read below and decide for yourself if your system needs the extra protection of Duratherm.

Anti Oxidants

Critical to any application that is not sealed from the atmosphere. If you don't have a nitrogen blanket on your expansion tank or reservoir it is crucial that your fluid contain an anti-oxidant. Oxidation leads to sludge formation which left unchecked could cause blockages and lead to complete system failure. Our fluids contain a proprietary dual stage anti-oxidant. See for yourself the difference this additive makes through our Competitive Comparison Report.

Corrosion Inhibitors

Most systems at some point in time will have water contamination. Whether from leaky heat exchangers or drawn from humid air, moisture venting through the expansion tank or oil reservoir can lead to corrosion inside the tank. Our corrosion inhibitors virtually eliminate the chance for corrosion.

Defoaming Agents

During start up air can become trapped in a system. As you pump this creates air bubbles (foaming) which can lead to pump cavitations possibly damaging pumps and other system components. Our proprietary additive package contains defoaming agents to help keep air from foaming in the oil.

Seal and Gasket Extender

High temperature applications are hard on seal and gasket materials, our seal and gasket extenders help fight heat damage that can cause premature seal failure. You pay a lot for high temperature seals; don't you want them to last as long as possible?

Suspension Agents

Some fluids after years of use tend to develop carbon and other particulate matter, even new systems have weld slag, metal shavings etc. that can become trapped in instrument lines or cause problems in other areas. Our suspension agents help to ensure particulate is held in suspension and easily filtered or caught in strainers.

Metal Deactivators

Some metals used in the construction of heat transfer systems can actually react with the oil causing premature breakdown. Our metal deactivators ensure compatibility with any system even those with copper lines, heat exchangers or fittings.

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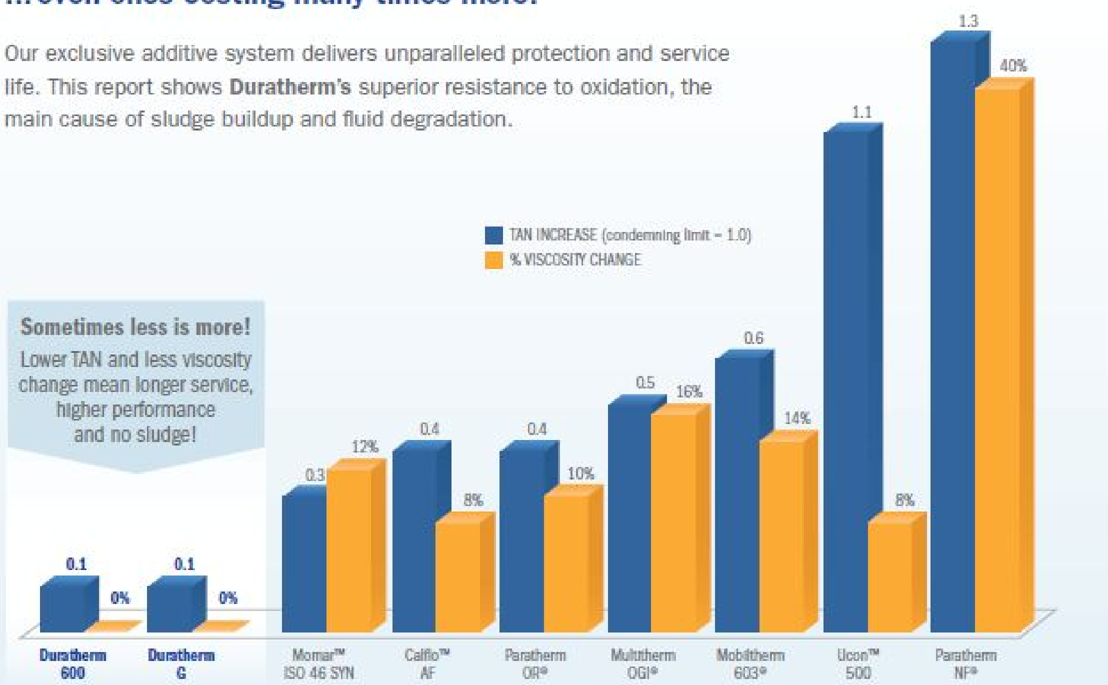
DURATHERM
HEAT TRANSFER FLUIDS

COMPETITORS REPORT

Our Fluids Outlast All Others

… even ones costing many times more!

Our exclusive additive system delivers unparalleled protection and service life. This report shows **Duratherm's** superior resistance to oxidation, the main cause of sludge buildup and fluid degradation.



ABOUT THE TEST

We chose 6 competing products*, ranging from low budget hot oils to some of the more expensive premium fluids from Exxon Mobil Corporation®, Dow Chemical Company®, Paratherm Corporation®, Petro-Canada Inc®, Momar® and Multitherm LLC®.

ABOUT THE METHOD

IP48 is an International Petroleum test standard in which 40ml of fluid is exposed to 400°F with 15L/h of air blown through the samples for 24 hours. This accelerates the aging process and shows a fluid's resistance to oxidation.

* **FLUIDS TESTED : Calflo AF®** - lot #044945 | **Duratherm G** - lot #058448 | **Duratherm 600** - lot #058689 | **Mobiltherm 603®** - lot #M19K9A3
Multitherm OG1® - lot#03/3318/115999 | **Paratherm OR®** - lot # CN4060031-L12 | **Paratherm NF®** - lot #CN4000042-802 | **Ucon 500®** - lot # 335073 #058689

1-800-446-4910 www.heat-transfer-fluid.com

DURATHERM
EXTENDED LIFE FLUIDS

TECHNOLOGY

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DURATHERM
EXTENDED LIFE FLUIDS

TECHNICAL PAPER

UNDERSTANDING FLUID DEGRADATION

Oxidative Degradation (Most common)

The scientific definition of oxidative degradation is the reaction of oxygen (in air) with the fluid by a free radical mechanism to form larger molecules which end up as polymers or solids. These thicken the fluid increasing its viscosity. A more viscous fluid will be more difficult to pump, have poorer heat transfer characteristics as well as an increased chance of coke formation. Oxidation is also accompanied by an increase in the acidity (TAN) of the fluid. As with most chemical reactions, oxidation occurs more rapidly as the temperature is increased. At room temperature the reaction rate is hardly measurable. However, at elevated temperatures the affect is exponential and can impact the fluid life in systems not utilizing oxidation reducing measures such as nitrogen blanketing the expansion tank.

In layman terms oxidation occurs when hot fluid comes in contact with air. Signs of fluid oxidation are seen most evident as sludge formation within the system especially in low flow areas such as reservoirs or expansion tanks. Total Acid Number (n/t-H) The common measurement of oxidative degradation is TAN. TAN will increase as fluids experience oxidative degradation. These acids will promote sludge and resin formation. TAN values above the range of 1.0 to 1.5 mg KOH/g are usually a cause for concern. It is important to note that with smaller less efficient draining systems these acids can remain behind and contaminate new fluids. It is extremely important especially if the TAN number is greater than 1.0 to ensure maximum evacuation of the spent fluid prior to refilling.

Thermal Degradation

Thermal degradation or thermal cracking is the breaking of carbon - carbon bonds in the fluid molecules by heat in excess of the fluids recommended maximum bulk temperture. The reaction may either stop at that point, in which case smaller molecules than previously existed are formed, or, the fragments may react with each other to form polymeric molecules larger than previously existed in the fluid. In heat transfer terminology, the two types of degradation products are known as "low boilers" and "high boilers".

Low Boilers

The effect of the low boilers is to decrease the flash point and viscosity of the fluid as well as to increase its vapor pressure. The increased vapor pressure can affect overall system efficiency and can cause pump cavitation. The reduction in the flash point could also be cause for safety concerns.

High Boilers

If thermal degradation occurs at extreme temperatures greater than 400°C (752°F), the effect is not only to break carbon - carbon bonds but to separate hydrogen atoms from carbon atoms and form coke. The effect of the high boilers is to increase the viscosity of the fluid as long as they remain in solution. However, once their solubility limit is exceeded, they begin to form solids which can foul the heat transfer surfaces. In this case, fouling of the heat transfer surfaces is very rapid and the system will soon cease to operate.

In layman terms, thermal degradation is overheating the oil past its boiling point. As the fluid boils, much like water, it produces a lighter component in the form of vapors. Excessive overheating or cracking can cause reduced viscosity as well as pose safety concerns with the creation of the lighter components which in turn reduces the overall flash point, fire point and autoignition temperatures.

Flash Point

The flash point is important from the viewpoint of safety; however, it is not a concern unless it falls below 120°CC (248°F). It is quite common for heat transfer systems to be operated at temperatures above the flash point of the fluid.

"what our customers are saying"

The differences from the old Calflo heat transfer fluid and the Duratherm 600 product was amazing. The performance of the Duratherm product was working so well at our plant ...I called the other plants ...they are looking into switching over to Duratherm.

—J. Gerbec, Maintenance Manager, Cantex Inc.

We have been using Duratherm 600 in our hot oil systems, and Duratherm G in our open oil baths, since 2003. Since then **our oxidation problems have disappeared** and we have had no issues of any kind with these fluids... **You manufacture products that perform exactly as advertised,** which is not always the case in the marketplace.

—H. Blair, Maintenance Coordinator, Saint-Gobain Crystals and Detectors

Since we changed over to the Duratherm, **I've had zero pump and valve failures in over a year and a half.** We used to have to roto-rooter the heater zones due to clogging, this hasn't been a problem since we switched. **Actually the heat transfer appears to be the best it's ever been.**

—R. Barnett, Maintenance Manager, Nursery Supplies Inc.

Since the switch to Duratherm G (from Ucon 500) we have increased the time between oil changes and nearly eliminated any issues.... **the price of Duratherm G is not only less expensive by the drum but the longer life saves money in the long run.** I would recommend it to anyone using Ucon 500.

—J. Smith Maintenance Manager, Azek Building Products

We were thoroughly impressed, the system was spotless, all of the hard buildup completely removed in 6 hours to a degree that we thought was unattainable without sending units out to be tank cleaned. **We then filled the unit with Duratherm and haven't had a single issue with this unit since.**

—M. Fransiscovich, Maintenance American Pipe and Plastics

The difference is clear – literally! We have had one of the baths in use for approximately 3 months and the fluid is still clean and clear... Yet another bonus was that the pricing was below comparable heat transfer fluids. **I would certainly recommend Duratherm G to anyone in need of a reliable heat transfer fluid.**

—S. Bailey Sr. Lab Technician, Parker Hannifin Corporation

We have been using it (Duratherm) in our oil jacketed extruder as a heat transfer fluid for over a year now with no problems. We generally run between 180 and 190 C and often run for months between shut-downs. The oil still looks as clear as it did when we first put it into use. **I am very pleased with the product and would buy it again if it ever wears out, but that might be a while!**

—J. Thomas, Director of Metal Injection Molding, Continuous Metal Technology

I am very happy with the way your Duratherm 600 fluid has performed for us on a day to day basis. As you also are aware I tried your Duraclean and Carb off products. **These performed exceptionally well for us and did exactly what your team said they would do for us.**

—S. Poletto, Maintenance Manager, leading bottle and packaging company

1 800 446 4910 • www.heat-transfer-fluid.com

DURATHERM
EXTENDED LIFE FLUIDS

DURATHERM EXTENDED LIFE FLUIDS
P.O. Box 563, Lewiston, NY 14092
Ph: 800-446-4910 / Fax: 905-984-6684
Web: www.heat-transfer-fluid.com

Material Safety Data Sheet

according to 1907/2006 EC, Article 31

Duratherm 450
High Temperature Heat Transfer Fluid

Revision Date: 01/2011
Revision #: 1

1. IDENTIFICATION OF THE SUBSTANCE / PREPARATION AND THE COMPANY

Product Name	Duratherm 450 - High Temperature Heat Transfer Fluid
Company Name	Duratherm Extended Life Fluids P.O. Box 563, Lewiston, NY 14092
Telephone	800-446-4910
Fax	905-984-6684
Website	www.heat-transfer-fluid.com
Emergency telephone number	800-446-4910

2. HAZARDS IDENTIFICATION

Physical Sate	Viscous Liquid
Odor	Very slight hydrocarbon odor
HMIS (Canada)	Not controlled under HMIS (Canada)
OSHA/HCS Status	This material is not considered hazardous by OSHA Hazard Communication Standard (29 CFR 1910.1200. Refer to and retain this MSDS for safety and handling information
Emergency Overview	No specific hazard
Routes of Enter	Dermal contact, eye contact, inhalation, ingestion
Potential Acute Health Effect	
Inhalation	No known significant effects or critical hazards
Ingestion	No known significant effects or critical hazards
Skin	No known significant effects or critical hazards
Eyes	No known significant effects or critical hazards
Potential Chronic Health Effect	
Chronic Effects	No known significant effects or critical hazards
Carcinogenicity	Not listed as a carcinogenic by OSHA, NTP, or IARC
Mutagenicity	No known significant effects or critical hazards
Teratogenicity	No known significant effects or critical hazards
Development Effects	No known significant effects or critical hazards
Fertility Effects	No known significant effects or critical hazards
Medical Conditions Aggravated by Overexposure	Repeated or prolonged exposure with spray or mist may produce chronic eye irritation and severe skin irritation. Repeated skin exposure can produce local skin destruction or dermatitis

3. COMPOSITION / INFORMATION ON INGREDIENTS

Description	This product does not contain any substances classified as hazardous to health

Material Safety Data Sheet - Duratherm 450 - Contd.

Revision #: 1

4. FIRST AID MEASURES

Skin contact	Wash affected areas thoroughly with soap and water. Wash contaminated clothing before reuse. See medical attention if irritation or symptoms persist
Eye contact	Flush with clean, lukewarm water (low pressure) occasionally lifting eyelids. Seek physician assessment if eyes are inflamed.
Inhalation	Avoid breathing oil mists. Remove to fresh air. Give artificial respiration if not breathing. Oxygen may be given by qualified personnel if breathing is difficult. Get medical attention.
Ingestion	Do not induce vomiting. Force fluid. Has laxative effect.

5. FIRE FIGHTING MEASURES

Extinguishing media	For small fires: Carbon dioxide (CO_2) Dry chemical. Foam. Water spray.
Fire hazards	LOW FIRE HAZARD - Do not cut, drill, or weld empty containers
Protective equipment	Wear suitable respiratory equipment when necessary.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions	Ensure adequate ventilation of the working area.
Environmental precautions	Do not allow product to enter drains. Prevent further spillage if safe.
Clean up method	Absorb with inert, absorbent material. Transfer to suitable, labelled containers for disposal. Clean spillage area thoroughly with plenty of water.

7. HANDLING AND STORAGE

Handling	Avoid contact with eyes and skin. Ensure adequate ventilation of the working area. Adopt best Manual Handling considerations when handling, carrying and dispensing.
Storage	Keep in a cool, dry, well ventilated area. Keep containers tightly closed. Store in correctly labelled containers. Store at a maximum of 40°C.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Engineering measures	Ensure adequate ventilation of the working area.
Occupational exposure contr.	Keep away from food, drink and animal feed.
Respiratory protection	Normally not necessary. If mist is generated, wear approved organic vapor respirator suitable for oil mist areas with sufficient oxygen.
Skin/Hand Protection	Normally none required, for direct contact of more than 2 hours, PVC, Viton, or Nitrile gloves are recommended.
Eye protection	Normally none required, chemical goggles if splashing is likely or high pressure systems are used.
Ventilation	General ventilation
Exposure limits	Practically non-toxic ACGIH TL (United States). Notes: (Oil Mist) TWA: 5mg/m³, 8 hour(s) / STEL: 10 mg/m³ 15 minute(s)
Protective equipment	Protect clothing from contact with the product.

9. PHYSICAL AND CHEMICAL PROPERTIES

Description	Liquid
Color	Clear Liquid
Odor	Very slight hydrocarbon odor
Boiling point	>470°F (>248°C)
Flash point	>300°F (>149°C)
Vapor pressure	<0.003 kPa @ 25°C
Specific Gravity	0.84 - 0.92
Volatilies, % Volume	0%
Solubility in water	Negligible
Evaporation rate	Nil
Viscosity @40 °C (cSt)	Varies depending on grade

Material Safety Data Sheet - Duratherm 450 - Contd.

Revision #: 1

10. STABILITY AND REACTIVITY	
Stability	Stable under normal conditions.
Hazardous polymerization	Will not occur
Materials to avoid	Strong oxidizing agents.
Decomposition products	Analogous compounds evolve, carbon monoxide, carbon dioxide, and other undefined fragments.
11. TOXICOLOGICAL INFORMATION	
General	Acute Toxicity (LD_{50}): LD_{50} (oral, rabbit):> 5000 mg/kg LD_{50} (dermal, rat): > 2000 mg/kg LD_{50} (inhalative, rat):> 2500 mg/kg/4h
Other	In case of inhalation: no data available **Skin contact:** no data available **Eye contact:** no data available **Ingestion:** no data available **Irritation:** skin and eye irritating **Sensitization:** no sensitizing effects known **Subacute toxicity:** Intensive or prolonged exposition. Repeated or prolonged exposure with spray or mist may product chronic eye irritation and severe skin irritation. Repeated skin exposure can produce local skin destruction or dermatitis. **Chronic Toxicity:** not available **Subchronic Exposure:** not available **Specific symptoms observed in animal studies:** no data available **CMR Effects:** **Carcinogenity:** no data available **Reproductive toxicity:** no data available **Mutagenicity:** no data available **Summarized evaluation of the CMR properties:** not available
12. ECOLOGICAL INFORMATION	
Ecological Information	Do not allow to enter sewer/soil/surface or ground water **Ecological Information:** LC50 (Rainbow Trout): > 100 000 MG/1/96 h **Mobility:** no data available **Persistence and biodegradation:** not readily biodegradable **Bioaccumulation potential:** no data available **Results of PBT assessments:** no data available **Other adverse side effects:** no data available
13. DISPOSAL CONSIDERATIONS	
General information	Used product must be disposed of in accordance with Federal, State, and Local environmental control regulations. Incineration is preferred. DO NOT HEAT OF CUT EMPTY CONTAINER WITH ELECTRIC OR GAS TORCH.
14. TRANSPORTATION INFORMATION	
Technical Name	Severely Hydrocracked Paraffinic Hydrocarbon
D.O.T. hazard class	Not regulated
U.N. N.A. #	Not regulated
Product label	Duratherm 450 - Duratherm High Temperature Heat Transfer Fluid

Material Safety Data Sheet - Duratherm 450 - Contd.

Revision #: 1

15. REGULATORY INFORMATION

EU Risk phrases	NSH - No Significant Hazard This product is not classified according to EU regulations
HMIS	Not controlled under HMIS (Canada)
EC Classification	Not classified as dangerous under EC classsifications
EC Symbols	Not classified
OSHA status	Non Hazardous under 29 CFR 1910.1200
TSCA status	N/A
RCRA status	If discarded in its purchased form this product would not be a hazardous waste either by listing or characteristic. However it is the responsibility of the product user to determine at the time of disposal, whether the material being disposed of is a hazardous waste (40 CFR 261.20-24).
Other Information	Environmental Protection Act 1990 (as amended). Health and Safety at Work Act 1974. Consumers Protection Act 1987. Control of Pollution Act 1974. Environmental Act 1995. Factories Act 1961. Carriage of Dangerous Goods by Road and Rail (Classification, Packaging and Labelling) Regulations. Chemicals (Hazard Information and Packaging for Supply) Regulations 2002. Control of Substances Hazardous to Health Regulations 1994 (as amended). Road Traffic (Carriage of Dangerous Substances in Packages) Regulations. Merchant Shipping (Dangerous Goods and Marine Pollutants) Regulations. Road Traffic (Carriage of Dangerous Substances in Road Tankers in Tank Containers) Regulations. Road Traffic (Training of Drivers of Vehicles Carrying Dangerous Goods) Regulations. Reporting of Injuries, Diseases and Dangerous. Other Regulations. Health and Safety (First Aid) Regulations 1981. Personal Protective Equipment (EC Directive) Regulations 1992. Personal Protective Equipment at Work Regulations 1992.

OSHA status	Non Hazardous under 29 CFR 1910.1200
TSCA status	N/A
RCRA status	If discarded in its purchased form this product would not be a hazardous waste either by listing or characteristic. However it is the responsibility of the product user to determine at the time of disposal, whether the material being disposed of is a hazardous waste (40 CFR 261.20-24).
HMIS status	

Health Hazard	1
Fire Hazard	1
Reactivity	0
Personal Protection	B

NFPA (U.S.A.)

Rating
0= Insignificant,
1=Slight,
2=Moderate,
3= High,
4= Extreme

16. OTHER INFORMATION

Further information	This information is furnished without warranty, expressed or implied, except that it is accurate to the best knowledge of Duratherm Extended Life Fluids. The data on this sheet related only to the specific material designed herein. Duratherm Extended Life Fluids assumes no legal responsibility for the use or reliance upon these data.

DURATHERM
EXTENDED LIFE FLUIDS

DURATHERM 450

PROPERTY VS. TEMPERATURE CHART

DURATHERM 450
STANDARD

TEMPERATURE (Fahrenheit)	DENSITY (lb/ft3)	KINEMATIC VISCOSITY (Centistoke)	DYNAMIC VISCOSITY (Centipoise)	THERMAL CONDUCTIVITY (BTU/hr-F-ft)	HEAT CAPACITY (BTU/lb.F)	VAPOUR PRESSURE (Psia)
10	55.22	40.50	35.82	0.084	0.474	0.00
20	54.99	28.70	25.28	0.084	0.478	0.00
30	54.75	21.20	18.59	0.084	0.482	0.00
40	54.51	16.20	14.15	0.083	0.486	0.00
50	54.28	12.70	11.04	0.083	0.490	0.04
60	54.04	10.20	8.83	0.083	0.494	0.05
70	53.81	8.40	7.24	0.083	0.498	0.06
80	53.57	7.00	6.01	0.082	0.502	0.07
90	53.33	5.90	5.04	0.082	0.506	0.08
100	53.10	5.10	4.34	0.082	0.510	0.09
110	52.86	4.40	3.73	0.082	0.510	0.10
120	52.62	3.90	3.29	0.082	0.518	0.11
130	52.39	3.50	2.94	0.081	0.522	0.12
140	52.15	3.10	2.59	0.081	0.526	0.13
150	51.91	2.80	2.33	0.081	0.530	0.14
160	51.68	2.50	2.07	0.081	0.534	0.15
170	51.44	2.30	1.90	0.080	0.538	0.17
180	51.21	2.10	1.72	0.080	0.542	0.18
190	50.97	2.00	1.63	0.080	0.546	0.20
200	50.73	1.80	1.46	0.080	0.550	0.21
210	50.00	1.70	1.36	0.079	0.554	0.23
220	50.26	1.60	1.29	0.079	0.558	0.25
230	50.02	1.50	1.20	0.079	0.562	0.28
240	49.79	1.40	1.12	0.079	0.566	0.30
250	49.55	1.30	1.03	0.079	0.570	0.33
260	49.31	1.20	0.95	0.078	0.574	0.37
270	49.08	1.20	0.94	0.078	0.578	0.41
280	48.84	1.10	0.86	0.078	0.582	0.46
290	48.61	1.10	0.86	0.078	0.586	0.52
300	48.37	1.00	0.77	0.077	0.590	0.58
310	48.13	1.00	0.77	0.077	0.594	0.65
320	47.90	0.90	0.69	0.077	0.598	0.73
330	47.66	0.90	0.69	0.077	0.602	0.82
340	47.42	0.80	0.61	0.077	0.606	0.92
350	47.19	0.80	0.60	0.076	0.610	1.03
360	46.95	0.80	0.60	0.076	0.614	1.16
370	46.71	0.80	0.60	0.076	0.618	1.30
380	46.48	0.70	0.52	0.076	0.622	1.45
390	46.24	0.70	0.52	0.075	0.626	1.63
400	46.00	0.70	0.52	0.075	0.630	1.83
410	45.77	0.70	0.51	0.075	0.634	2.05
420	45.53	0.60	0.44	0.075	0.638	2.29
430	45.30	0.60	0.44	0.074	0.642	2.57
440	45.06	0.60	0.43	0.074	0.646	2.88
450	44.82	0.60	0.43	0.074	0.650	3.23

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DURATHERM
EXTENDED LIFE FLUIDS

DURATHERM 450

PROPERTY VS. TEMPERATURE CHART

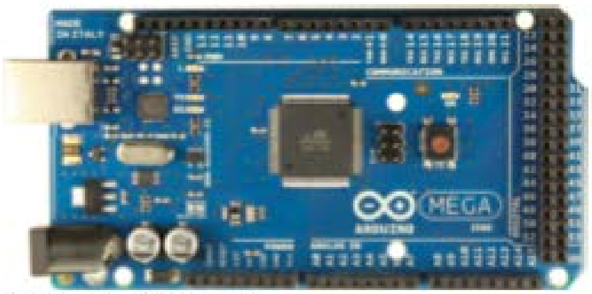
DURATHERM 450
METRIC

TEMPERATURE (Celsius)	DENSITY (kg/m3)	KINEMATIC VISCOSITY (centistokes)	DYNAMIC VISCOSITY (centipoise)	THERMAL CONDUCTIVITY (W/m.K)	HEAT CAPACITY (kJ/kg.K)	VAPOR PRESSURE (KPA)
-12	884.54	40.50	35.82	0.145	1.985	0.00
-7	880.85	28.70	25.28	0.145	2.001	0.00
-1	877.01	21.20	18.59	0.145	2.018	0.00
4	873.17	16.20	14.15	0.144	2.035	0.00
10	869.48	12.70	11.04	0.144	2.052	0.28
16	865.64	10.20	8.83	0.144	2.068	0.34
21	861.95	8.40	7.24	0.144	2.085	0.41
27	858.11	7.00	6.01	0.142	2.102	0.48
32	854.26	5.90	5.04	0.142	2.119	0.55
38	850.58	5.10	4.34	0.142	2.135	0.62
43	846.74	4.40	3.73	0.142	2.135	0.68
49	842.89	3.90	3.29	0.142	2.169	0.74
54	839.21	3.50	2.94	0.140	2.186	0.80
60	835.36	3.10	2.59	0.140	2.202	0.88
66	831.52	2.80	2.33	0.140	2.219	0.96
71	827.83	2.50	2.07	0.140	2.236	1.04
77	823.99	2.30	1.90	0.138	2.252	1.14
82	820.30	2.10	1.72	0.138	2.269	1.24
88	816.46	2.00	1.63	0.138	2.286	1.35
93	812.62	1.80	1.46	0.138	2.303	1.48
99	800.92	1.70	1.36	0.137	2.319	1.61
104	805.09	1.60	1.29	0.137	2.336	1.75
110	801.24	1.50	1.20	0.137	2.353	1.91
116	797.56	1.40	1.12	0.137	2.370	2.09
121	793.71	1.30	1.03	0.137	2.386	2.28
127	789.87	1.20	0.95	0.135	2.403	2.55
132	786.19	1.20	0.94	0.135	2.420	2.86
138	782.34	1.10	0.86	0.135	2.437	3.20
143	778.66	1.10	0.86	0.135	2.453	3.59
149	774.81	1.00	0.77	0.133	2.470	4.02
154	770.97	1.00	0.77	0.133	2.487	4.51
160	767.28	0.90	0.69	0.133	2.504	5.06
166	763.44	0.90	0.69	0.133	2.520	5.67
171	759.60	0.80	0.61	0.133	2.537	6.35
177	755.91	0.80	0.60	0.132	2.554	7.12
182	752.07	0.80	0.60	0.132	2.571	7.98
188	748.22	0.80	0.60	0.132	2.587	8.94
193	744.54	0.70	0.52	0.132	2.604	10.02
199	740.69	0.70	0.52	0.130	2.621	11.23
204	736.85	0.70	0.52	0.130	2.638	12.59
210	733.16	0.70	0.51	0.130	2.654	14.11
216	729.32	0.60	0.44	0.130	2.671	15.82
221	725.64	0.60	0.44	0.128	2.688	17.73
227	721.79	0.60	0.43	0.128	2.705	19.87
232	717.95	0.60	0.43	0.128	2.721	22.27

E. 5 Arduino Board Mega 2560

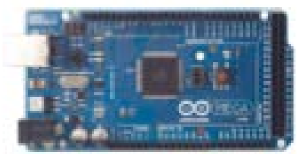
Arduino : Main / Arduino Board Mega 2560

Arduino Mega 2560

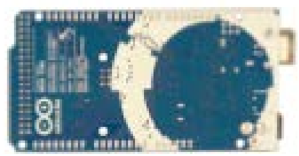


Arduino Mega 2560 R3 Front

Arduino Mega2560 R3 Back



Arduino Mega 2560 Front



Arduino Mega 2560 Back

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Overview

The Arduino Mega 2560 is a microcontroller board based on the ATmega2560 (datasheet). It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila.

The Mega 2560 is an update to the Arduino Mega, which it replaces.

Schematic, Reference Design & Pin Mapping

EAGLE files: arduino-mega2560_R3-reference-design.zip

Schematic: arduino-mega2560_R3-schematic.pdf

Pin Mapping: PinMap2560 page

Summary

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Power

The Arduino Mega can be powered via the USB connection or with an external power supply. The power source is selected automatically.

External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector.

The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The Mega2560 differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the ATmega16U2 (ATmega8U2 in the revision 1 and revision 2 boards) programmed as a USB-to-serial converter.
Revision 2 of the Mega2560 board has a resistor pulling the 8U2 HWB line to ground, making it easier to put into DFU mode.
Revision 3 of the board has the following new features:

- 1.0 pinout: added SDA and SCL pins that are near to the AREF pin and two other new pins placed near to the RESET pin, the IOREF that allow the shields to adapt to the voltage provided from the board. In future, shields will be compatible both with the board that use the AVR, which operate with 5V and with the Arduino Due that operate with 3.3V. The second one is a not connected pin, that is reserved for future purposes.
- Stronger RESET circuit.
- Atmega 16U2 replace the 8U2.

The power pins are as follows:

- **VIN.** The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- **5V.** This pin outputs a regulated 5V from the regulator on the board. The board can be supplied with power either from the DC power jack (7 - 12V), the USB connector (5V), or the VIN pin of the board (7-12V). Supplying voltage via the 5V or 3.3V pins bypasses the regulator, and can damage your board. We don't advise it.
- **3V3.** A 3.3 volt supply generated by the on-board regulator. Maximum current draw is 50 mA.
- **GND.** Ground pins.

Memory

The ATmega2560 has 256 KB of flash memory for storing code (of which 8 KB is used for the bootloader), 8 KB of SRAM and 4 KB of EEPROM (which can be read and written with the EEPROM library).

Input and Output

Each of the 54 digital pins on the Mega can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

- **Serial: 0 (RX) and 1 (TX); Serial 1: 19 (RX) and 18 (TX); Serial 2: 17 (RX) and 16 (TX); Serial 3: 15 (RX) and 14 (TX).** Used to receive (RX) and transmit (TX) TTL serial data. Pins 0 and 1 are also connected to the corresponding pins of the ATmega16U2 USB-to-TTL Serial chip.
- **External Interrupts: 2 (interrupt 0), 3 (interrupt 1), 18 (interrupt 5), 19 (interrupt 4), 20 (interrupt 3), and 21 (interrupt 2).** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.
- **PWM: 2 to 13 and 44 to 46.** Provide 8-bit PWM output with the analogWrite() function.
- **SPI: 50 (MISO), 51 (MOSI), 52 (SCK), 53 (SS).** These pins support SPI communication using the SPI library. The SPI pins are also broken out on the ICSP header, which is physically compatible with the Uno, Duemilanove and Diecimila.
- **LED: 13.** There is a built-in LED connected to digital pin 13. When the pin is HIGH value, the LED is on, when the pin is LOW, it's off.
- **TWI: 20 (SDA) and 21 (SCL).** Support TWI communication using the Wire library. Note that these pins are not in the same location as the TWI pins on the Duemilanove or Diecimila.

The Mega2560 has 16 analog inputs, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and analogReference() function.

There are a couple of other pins on the board:

- **AREF.** Reference voltage for the analog inputs. Used with analogReference().

- **Reset.** Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

Communication

The Arduino Mega2560 has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega2560 provides four hardware UARTs for TTL (5V) serial communication. An ATmega16U2 (ATmega 8U2 on the revision 1 and revision 2 boards) on the board channels one of these over USB and provides a virtual com port to software on the computer (Windows machines will need a .inf file, but OSX and Linux machines will recognize the board as a COM port automatically. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the board. The RX and TX LEDs on the board will flash when data is being transmitted via the ATmega8U2/ATmega16U2 chip and USB connection to the computer (but not for serial communication on pins 0 and 1).

A SoftwareSerial library allows for serial communication on any of the Mega2560's digital pins.

The ATmega2560 also supports TWI and SPI communication. The Arduino software includes a Wire library to simplify use of the TWI bus; see the documentation for details. For SPI communication, use the SPI library.

Programming

The Arduino Mega can be programmed with the Arduino software (download). For details, see the reference and tutorials.

The ATmega2560 on the Arduino Mega comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files).

You can also bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.

The ATmega16U2 (or 8U2 in the rev1 and rev2 boards) firmware source code is available in the Arduino repository. The ATmega16U2/8U2 is loaded with a DFU bootloader, which can be activated by:

- On Rev1 boards: connecting the solder jumper on the back of the board (near the map of Italy) and then resetting the 8U2.
- On Rev2 or later boards: there is a resistor that pulling the 8U2/16U2 HWB line to ground, making it easier to put into DFU mode. You can then use Atmel's FLIP software (Windows) or the DFU programmer (Mac OS X and Linux) to load a new firmware. Or you can use the ISP header with an external programmer (overwriting the DFU bootloader). See this user-contributed tutorial for more information.

Automatic (Software) Reset

Rather then requiring a physical press of the reset button before an upload, the Arduino Mega2560 is designed in a way that allows it to be reset by software running on a connected computer. One of the hardware flow control lines (DTR) of the ATmega8U2 is connected to the reset line of the ATmega2560 via a 100 nanofarad capacitor. When this line is asserted (taken low), the reset line drops long enough to reset the chip. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.

This setup has other implications. When the Mega2560 is connected to either a computer running Mac OS X or Linux, it resets each time a connection is made to it from software (via USB). For the following half-second or so, the bootloader is running on the Mega2560. While it is programmed to ignore malformed data (i.e. anything besides an upload of new code), it will intercept the first few bytes of data sent to the board after a connection is opened. If a sketch running on the board receives one-time configuration or other data when it first starts, make sure that the software with which it communicates waits a second after opening the connection and before sending this data.

The Mega2560 contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It's labeled "RESET-EN". You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line; see this forum thread for details.

USB Overcurrent Protection

The Arduino Mega2560 has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

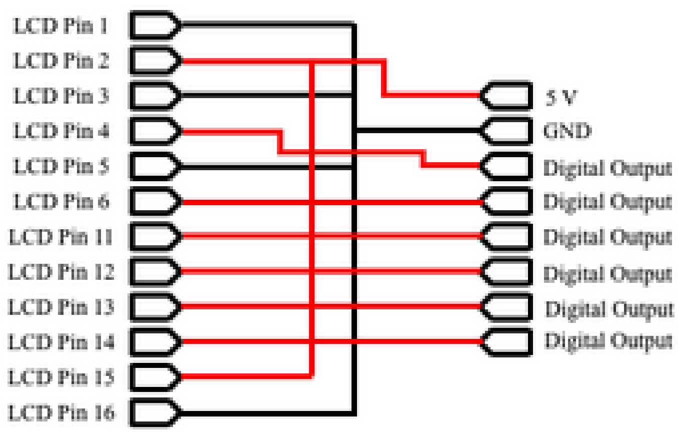
Physical Characteristics and Shield Compatibility

The maximum length and width of the Mega2560 PCB are 4 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Three screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

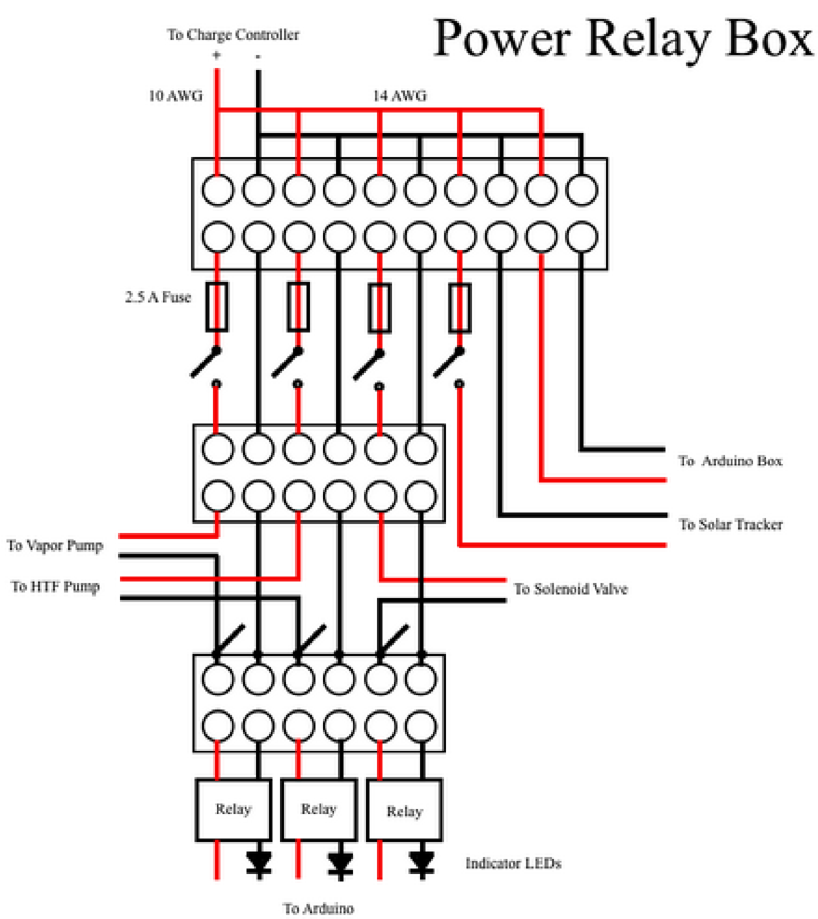
The Mega2560 is designed to be compatible with most shields designed for the Uno, Diecimila or Duemilanove. Digital pins 0 to 13 (and the adjacent AREF and GND pins), analog inputs 0 to 5, the power header, and ICSP header are all in equivalent locations. Further the main UART (serial port) is located on the same pins (0 and 1), as are external interrupts 0 and 1 (pins 2 and 3 respectively). SPI is available through the ICSP header on both the Mega2560 and Duemilanove / Diecimila. *Please note that I^2C is*

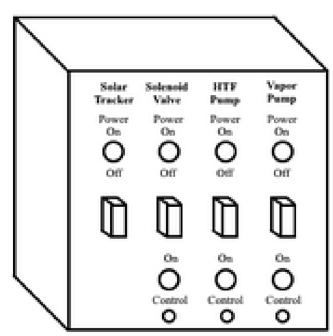
Appendix F: Wiring Diagrams/Schematics

F.1 LCD Wiring Schematic

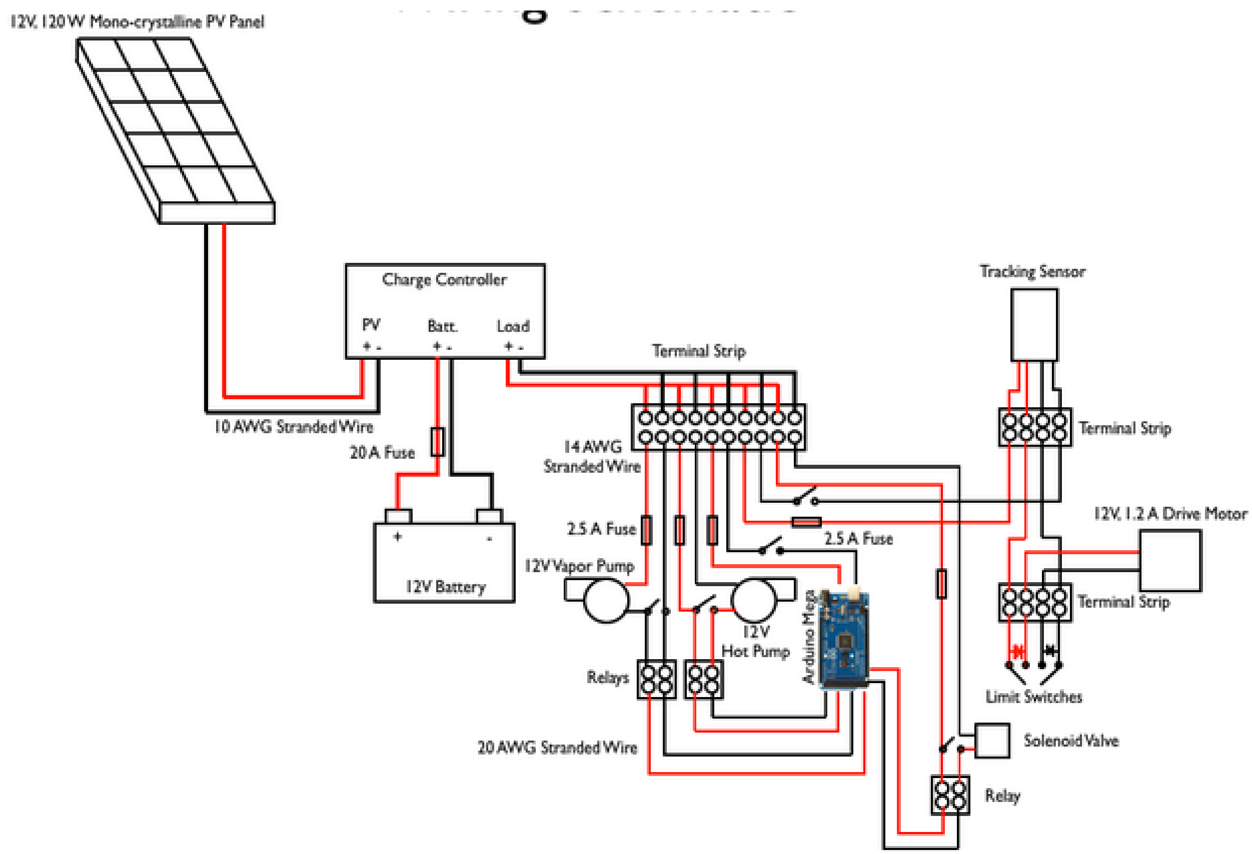


F.2 Power Switching Schematic



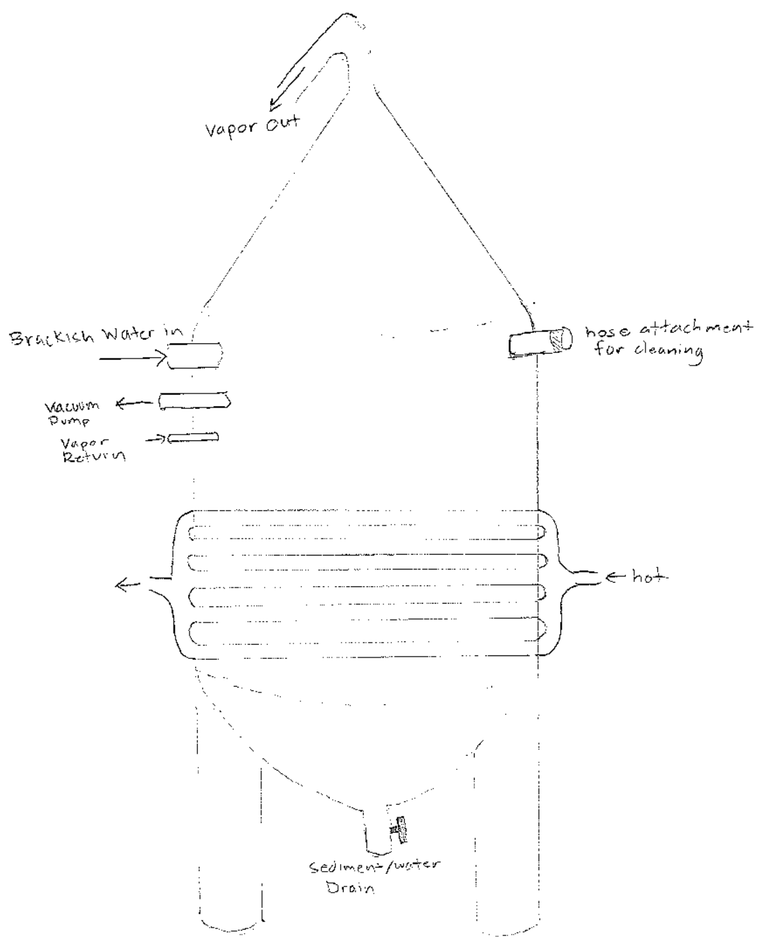


F.3 System Wiring Schematic



Appendix G: Conceptual Designs

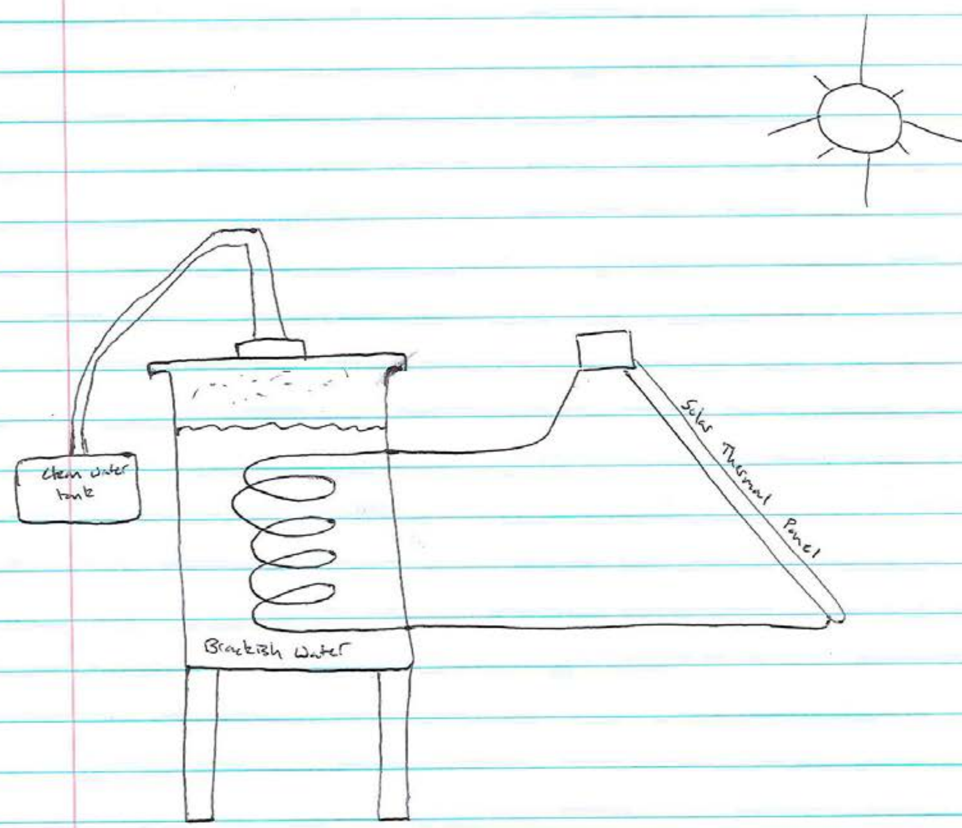
G.1 Large Boiler Design



- Larger heat exchanger to increase heat transfer
- Reposition brackish water inlet to top of the boiler
- Add hose attachment for easy cleaning
- Add drain at the bottom to ensure complete draining

G.2 Singular Boiler/Combined Salt-Water Storage Tank Design

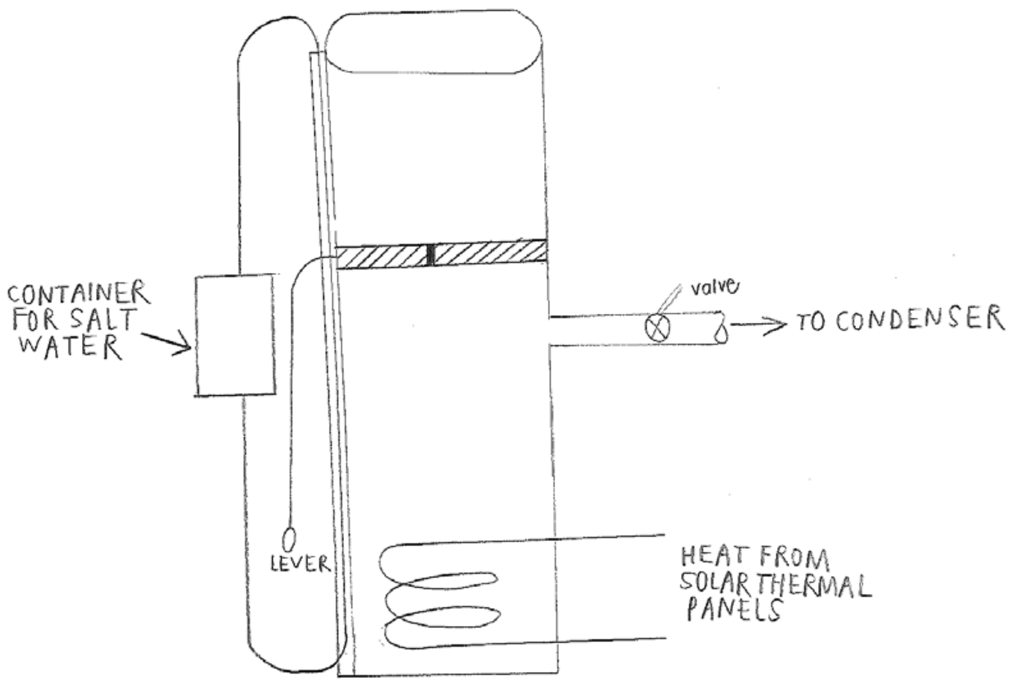
10/24/11



~~Use clea brackish water tank~~

Just use one tank ~~as~~ as heat exchanger and holding tank for brakish water. Therefore there would be no more brackish water tank but only a boiler.

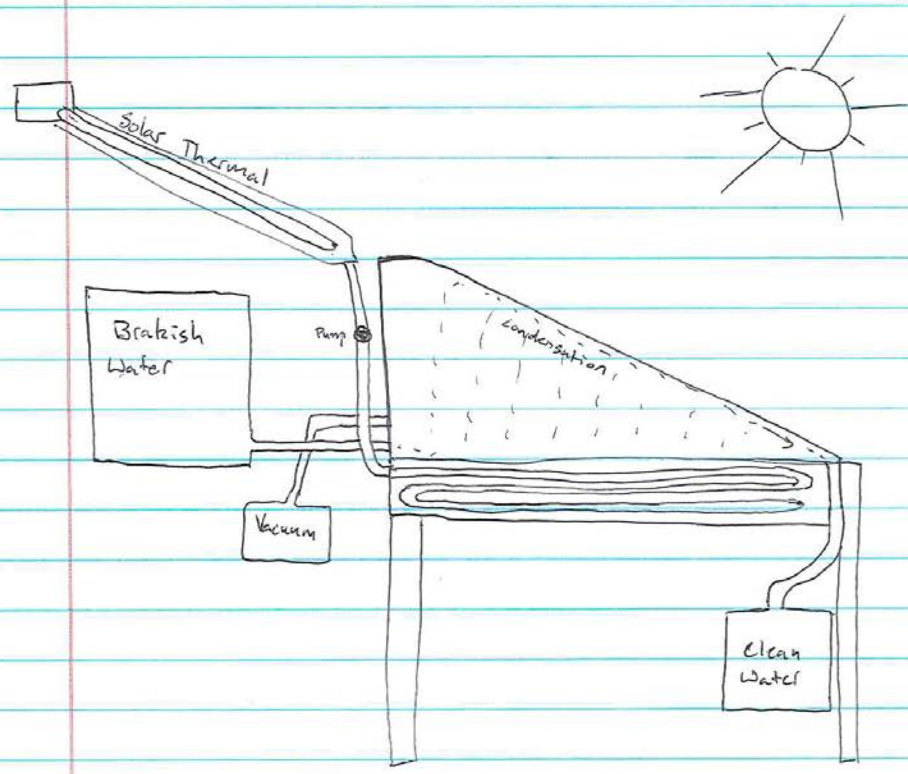
G.3 Vacuum Boiler Design



Research has proven that if water falls 10 m in a closed container, a vacuum can be created above it by gravity. This set-up has the user fill water to the top of this structure by the pulley container. once the top portion is filled, the top is sealed and lever is pulled to drop the water down. The system will then be able to heat water with lowered pressure. The vapor rises and goes down the pipe to the condenser.

G.4 Solar Still Boiler Design

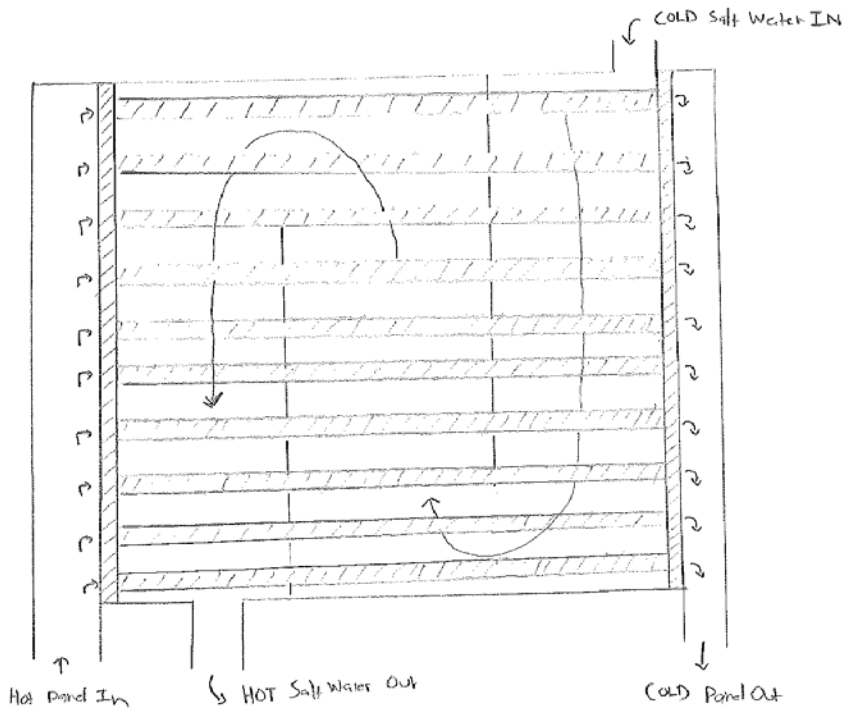
10/24/11



use solar still with heat exchanger at bottom to heat brackish water. Brackish water enters the vacuumed solar still and the solar thermal water heats up the brackish water to ~~expand~~ distill it faster. Condensation will build up on the roof of solar still and drop into a clean water tank

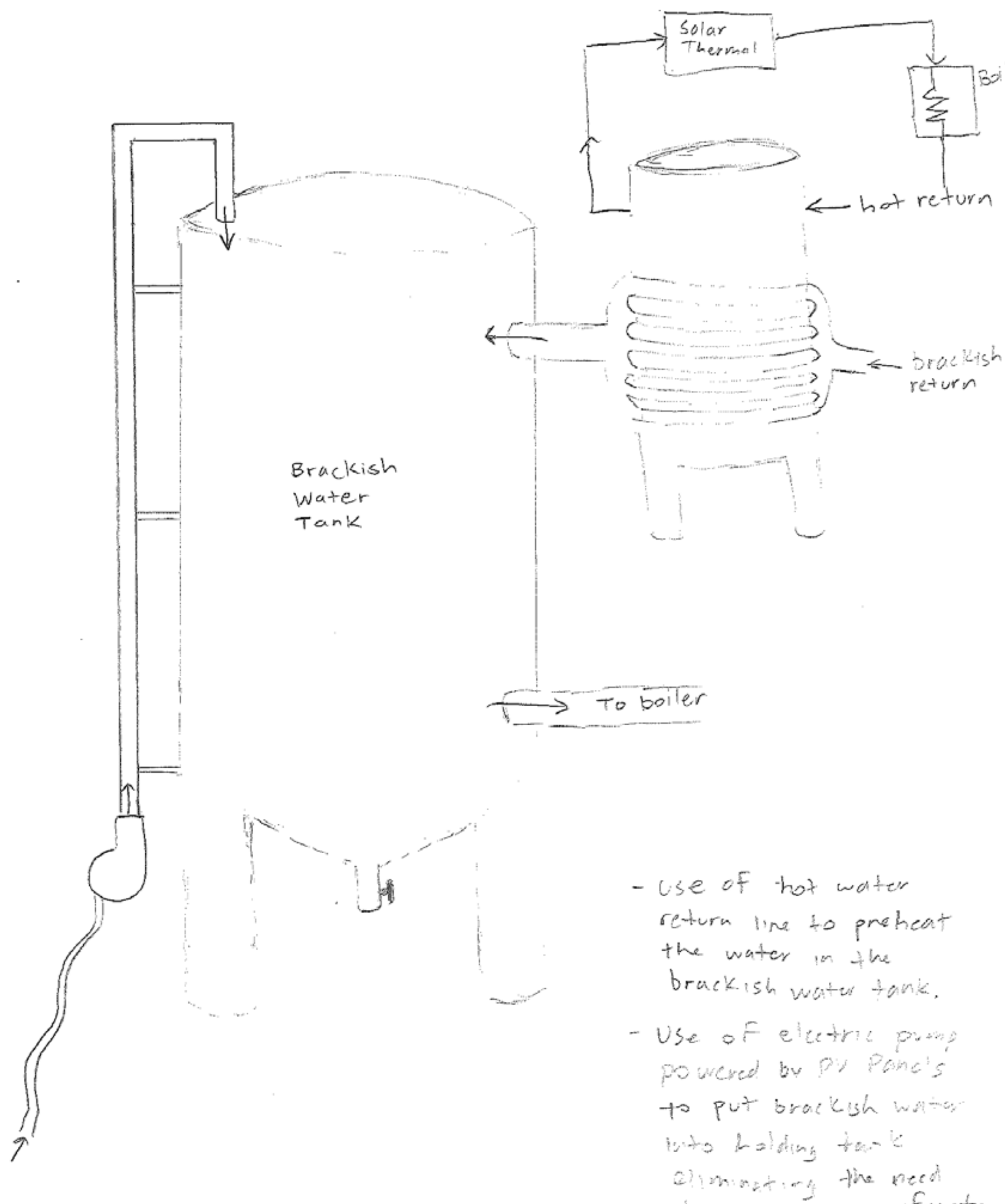
G.5 Shell and Tube Design

Heat Exchanger
(solar panel → salt water loop)



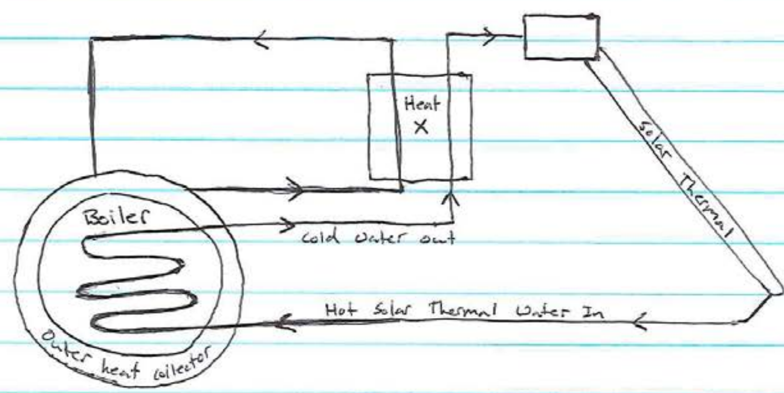
- Hot water from panel flows through tubes and warms cold salt water
- Counter-flow allows for higest possible salt water out temp.
- Winding path that salt water must flow increases distance and contact time allowing for more heat transfer.
- Design is fairly thin and can be attached flush to the back of a panel
- Heat exchange on the outside of the boiler allows for easier and more flexible boiler design.

G.6 Heat Storage Design



G.7 Outer Heat Collector Design

10/24/11

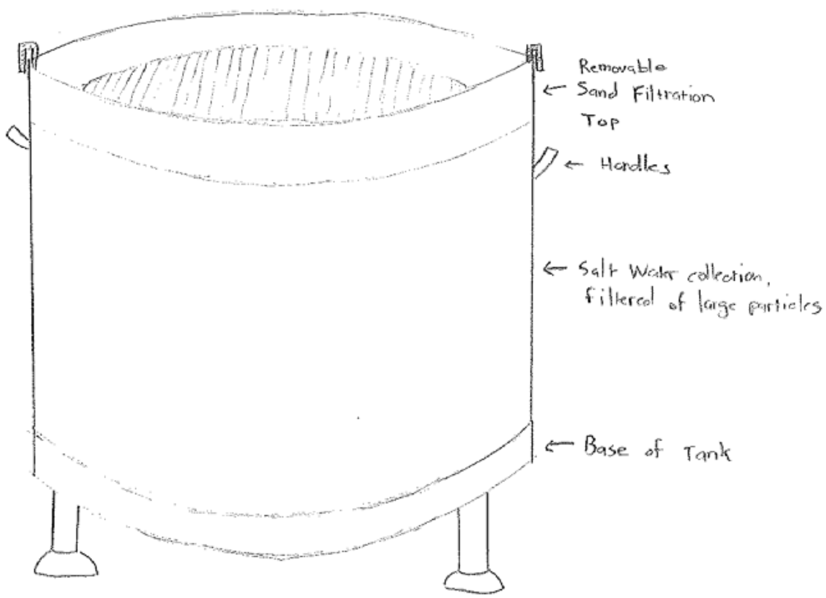


This design is to capture heat coming from the boiler. The dissipating heat will be collected using a fluid that transfers that heat back into the return solar thermal line in a heat exchanger

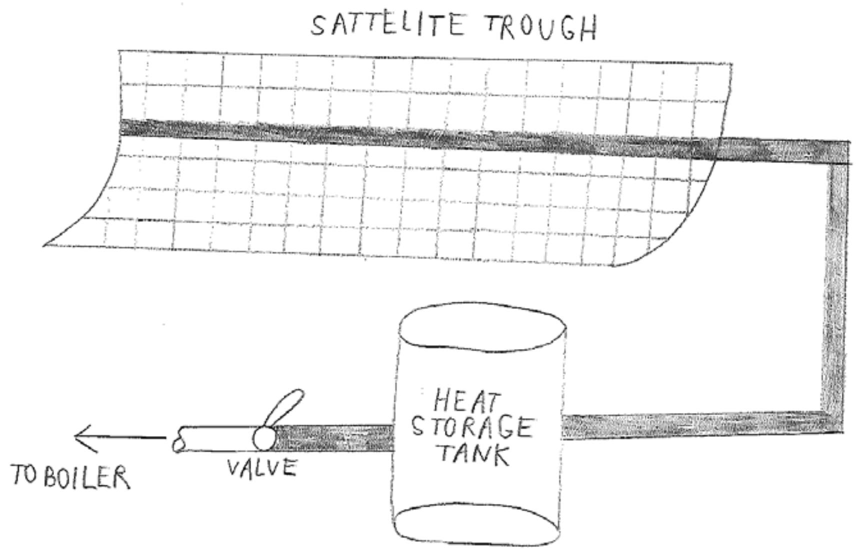
G.8 Salt Water Storage Tank Design

Salt Water Tank

- Our system is designed mainly for costal communities, meaning sand is easily accessible.
- Fine grade sand can be filled on the top of the tank allowing for effective filtration of large particles before the water is fed into the system
- Tank is low to the ground and removable from base allowing for easy cleaning, filling and replacement.

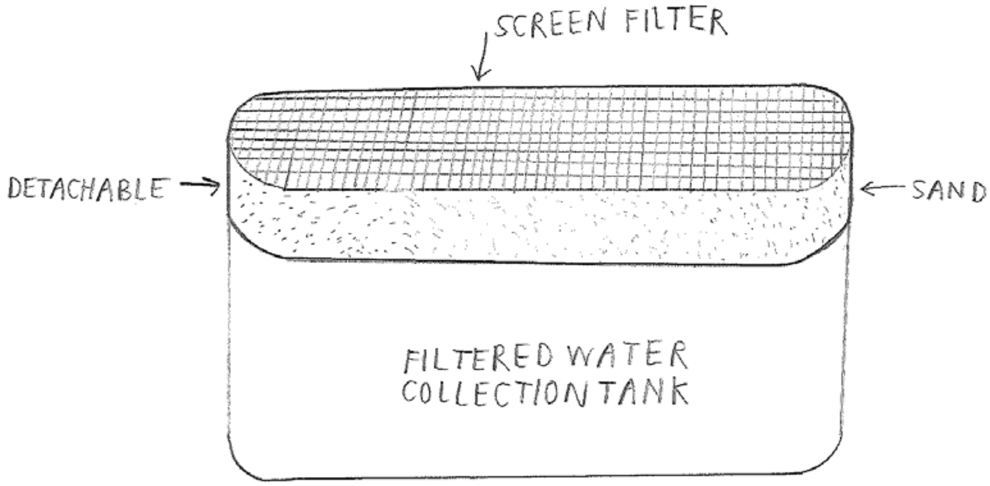


G.9 Solar Trough Design



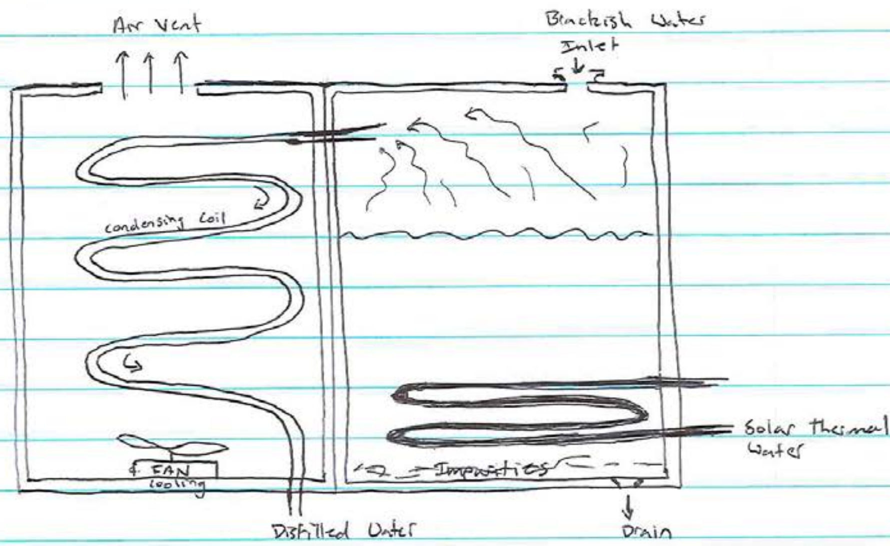
The sattelite trough can be made out of a reflective material (mirror) and a structural piece. A pipe will run through the center of the trough, catching the concentrated heat from the sun. This heat can then be fed into a heat storage tank (insulated) that is stored until later (valve closed). when the sun is no longer to provide for the system, the valve can be opened to provide heat for the system and power it. The valve controls heat to the boiler. The heat storage tank can use salt (as researched) to hold heat.

G.10 Screen Filter Design



To prevent the problem of large particles entering our system, we can prefilter the gathered water by running it thru this initial filter. The screen will catch large particles, such as leaves, rocks, and stick. The sand layer will catch smaller particles and the water that results would be clean of visible product that, had they not been removed, could have harmed the system.

G.11 Condenser Design

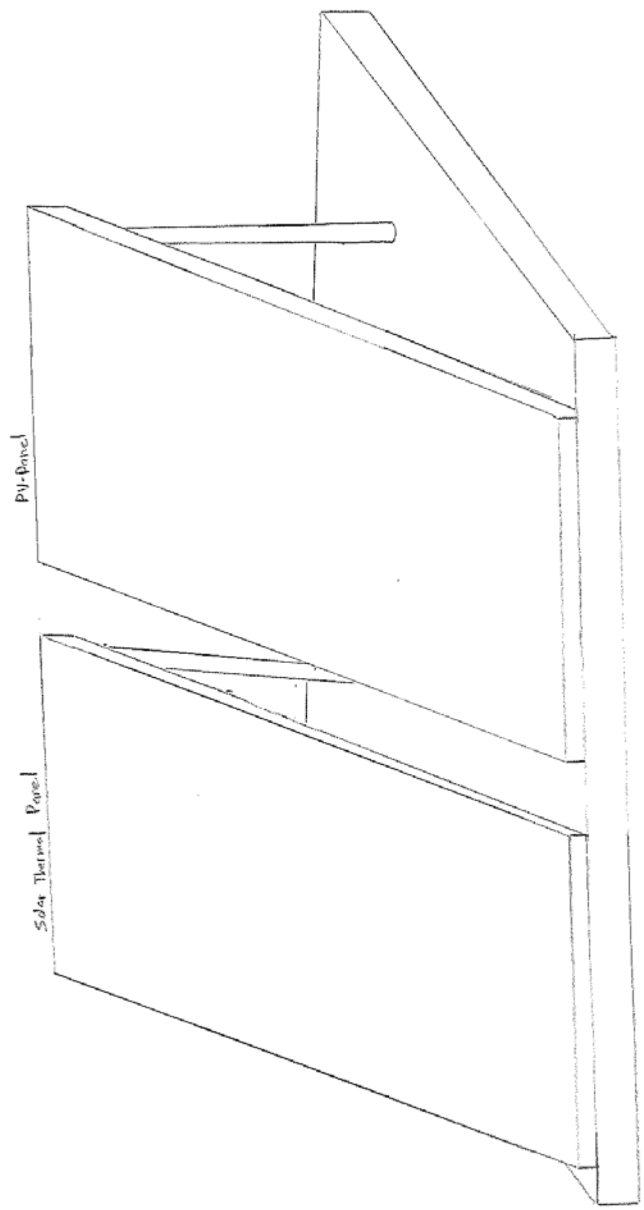


This design uses an evaporation chamber with a fan to cool down the water vapor in the condensing coil

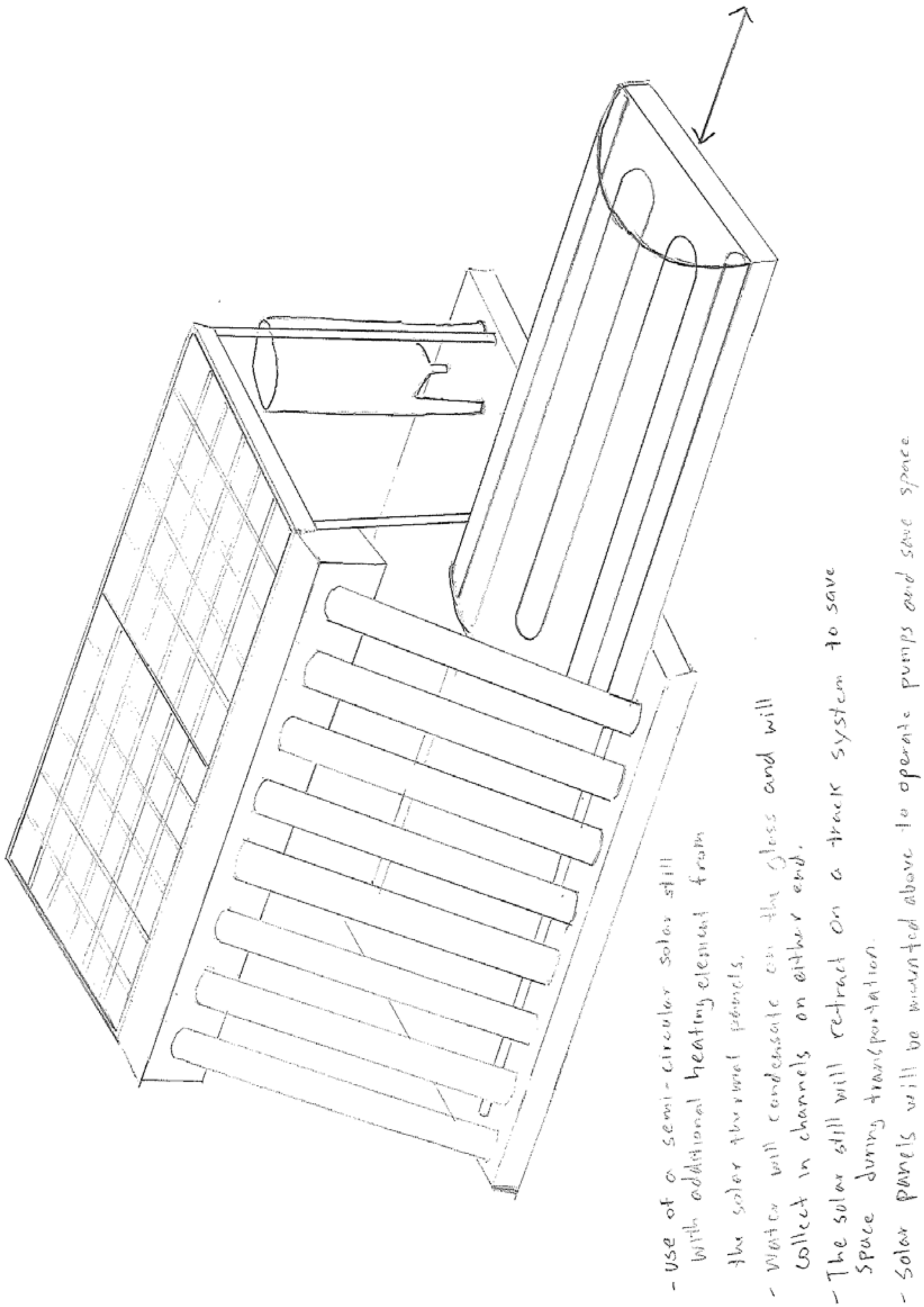
G.12 Collector and Solar Design

Split Array Energy Collection

- Energy is collected by both the solar thermal panel and the PV panel. Heated water from the solar thermal panel is used to heat brine water going into the boiler. The energy from the PV panel is used to power the system's pumps and can generate electricity that can be stored for night operation.



G.13 Semi-Circle Solar Design



Appendix H: Concept Scoring

H.1 Concept Scoring for Boiler Designs

Design Project = Solar Water Purification Syst **System=** Boiler

	TARGET or	DESIGN IDEAS									
CRITERIA	**FACTOR**	**1 = Baseline**		**2 = Large Boiler**		**3 = Singular Boiler**		**4 = Vacuum Boiler**		**5 =Solar Still Boiler**	
Time – Design	40	40		40		40		55		55	
Time – Build	60	60		40		55		100		100	
Time – Test	15	15		20		20		20		20	
Time Score	10		10		11.50		10.00		6.57		6.57
Cost – Prototype	$ 1,000	$ 1,000		$ 1,100		$ 1,100		$ 1,500		$ 1,500	
Cost – Production	$ 800	$ 800		$ 850		$ 900		$ 1,100		$ 1,100	
Cost Score	5		5		4.62		4.50		3.46		3.46
Safety	9	3	27	3	27	3	27	3	27	2	18
Resistance to Corrosion	9	3	27	5	45	5	45	5	45	5	45
Water Produciton	9	3	27	3	27	2	18	4	36	4	36
Low Maintanence	8.5	3	25.5	3	25.5	2	17	2	17	2	17
Life Expectancy	8.5	3	25.5	4	34	4	34	4	34	3	25.5
Ease of Use	8	3	24	4	32	5	40	4	32	3	24
Power Consumption	7.5	3	22.5	3	22.5	5	37.5	5	37.5	4	30
Portability	1.5	3	4.5	3	4.5	3	4.5	3	4.5	3	4.5
Size	1.5	3	4.5	2	3	2	3	1	1.5	2	3
Manufacturability	4	3	12	2	8	4	16	2	8	1	4
Water Capacity	3	3	9	4	12	4	12	3	9	3	9
	TOTAL		**223.5**		**256.6**		**268.5**		**261.5**		**226.0**
	RANK										
	% of MAX		83.2%		95.6%		100.0%		97.4%		84.2%
	MAX	**268.5**									

BASELINE = 2010-2011 Solar Water Purification System

Ideas

1 10-11 Solar Water System
2 Large Boiler
3 Singular Boiler
4 Vacuum Boiler
5 Solar Still Boiler

calculated
user input
fixed

H.2 Concept Scoring for Pre-Heat and Condenser Designs

Design Project = Solar Water Purification Syst **System=** Pre-Heat/Condenser

		DESIGN IDEAS									
	TARGET or										
CRITERIA	FACTOR	1 = Baseline		2 = Shell & Tube		3 = Heat Storage		4 = Outer Heat		5 = Combined Brackish Tank	
Time – Design	20	20		40		40		40		30	
Time – Build	10	10		50		40		40		25	
Time – Test	10	10		10		10		10		10	
Time Score	10		10		4.00		4.44		4.44		6.15
Cost – Prototype	$ 525	$ 525		$ 900		$ 900		$ 800		$ 400	
Cost – Production	$ 525	$ 525		$ 780		$ 780		$ 700		$ 400	
Cost Score	5		5		3.13		3.13		3.50		6.56
Safety	9	3	27	3	27	3	27	3	27	3	27
Resistance to Corrosion	9	3	27	4	36	4	36	4	36	4	36
Water Production	9	3	27	5	45	4	36	4	36	4	36
Low Maintanence	8.5	3	25.5	3	25.5	2	17	3	25.5	2	17
Life Expectancy	8.5	3	25.5	3	25.5	3	25.5	3	25.5	3	25.5
Ease of Use	8	3	24	3	24	3	24	3	24	3	24
Power Consumption	7.5	3	22.5	3	22.5	2	15	3	22.5	3	22.5
Portability	1.5	3	4.5	3	4.5	2	3	2	3	3	4.5
Size	1.5	3	4.5	2	3	1	1.5	2	3	3	4.5
Manufacturability	4	3	12	1	4	3	12	3	12	3	12
Water Capacity	3	3	9	5	15	4	12	3	9	4	12
	TOTAL		223.5		239.1		216.6		231.4		233.7
	RANK										
	% of MAX		93.5%		100.0%		90.6%		96.8%		97.7%
	MAX	239.1									

BASELINE = 2010-2011 Solar Water Purification System

calculated
user input
fixed

Ideas

1 10-11 Solar Water System
2 Shell & Tube Heat Exchanger
3 Heat Storage Tank
4 Outer Heat Collector
5 Combined Brackish Tank Collector

H.3 Concept Scoring for Heating Element Designs

Design Project = Solar Water Purification Syst **System=** Heating Element

	TARGET or	DESIGN IDEAS							
CRITERIA	**FACTOR**	**1 = Baseline**		**2 = Collector & Solar**		**3 = Solar Trough**		**4 = Semicircle Solar**	
Time – Design	10	10		40		45		30	
Time – Build	20	20		40		50		40	
Time – Test	10	10		15		15		15	
Time Score	10		10		4.21		3.64		4.71
Cost – Prototype	$ 1,000	$ 2,700		$ 3,200		$ 300		$ 3,500	
Cost – Production	$ 1,000	$ 2,700		$ 3,000		$ 275		$ 3,200	
Cost Score	5		13.5		4.35		46.96		4.03
Safety	9	3	27	3	27	3	27	3	27
Resistance to Corrosion	9	3	27	2.5	22.5	3	27	3	27
Water Production	9	3	27	3.5	31.5	4	36	3.5	31.5
Low Maintanence	8.5	3	25.5	2	17	3	25.5	2	17
Life Expectancy	8.5	3	25.5	3	25.5	3	25.5	3	25.5
Ease of Use	8	3	24	3	24	3	24	3	24
Power Consumption	7.5	3	22.5	3	22.5	3	22.5	3	22.5
Portability	1.5	3	4.5	1.5	2.25	3	4.5	3	4.5
Size	1.5	3	4.5	1	1.5	3	4.5	2	3
Manufacturability	4	3	12	2	8	2.5	10	1.5	6
Water Capacity	3	3	9	4.5	13.5	3	9	4.5	13.5
	TOTAL		**232.0**		**203.8**		**266.1**		**210.2**
	RANK								
	% of MAX		87.2%		76.6%		100.0%		79.0%
	MAX	**266.1**							

BASELINE = 2010-2011 Solar Water Purification System

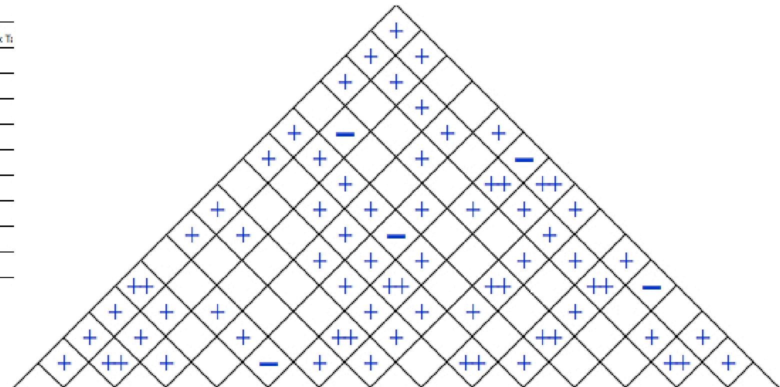
Ideas

1 10-11 Solar Water System
2 Collector & Solar Still
3 Solar Trough
4 Semicircle Solar Still

calculated
user input
fixed

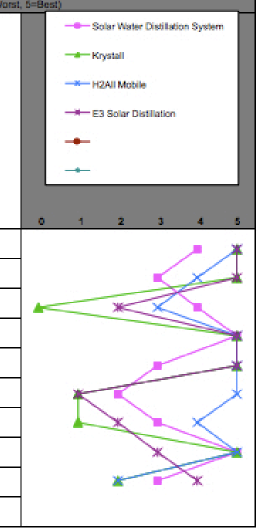
Appendix I: Quality Function Deployment (QFD)

Title:	Solar Water Distillation System
Author:	Alina Carlson, Andrew Nose, Reece Kiriu, Chris Sugii, Erin Taketa, Alex T
Date:	11/14/11
Notes:	



Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Construction Materials	# of Components	# of Moving Parts	Control Systems	Water Quality	Water Production	Insulation	Heat Exchange	Location of Use	Operating Conditions	Low Pressure	Atmospheric Pressure	Pump Flow Rates	Efficiency of Solar Collector	Length of Piping Used	Solar Water Distillation System	Krystall	H2AI Mobile	E3 Solar Distillation
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)			
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▼	▼	▼	▲	▲	▲	▲	▲	▲	x	x	▲	▲	▼				
1	9	13.2	8.5	Reliability	Θ	Θ	Θ	Θ	▲	O	▲	O	Θ	Θ	Θ	▲	Θ	O	O	4	5	5	5
2	9	12.4	8.0	Ease of Use	▲	Θ	Θ	Θ	▲	▲	▲	▲	▲	O	Θ	Θ	▲	▲	▲	3	5	4	5
3	9	10.1	6.5	Cost	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	O	Θ	O	Θ	Θ	Θ	4	0	3	2
4	9	17.1	11.0	Safety	Θ	O	Θ	Θ	Θ	▲	Θ	▲	O	Θ	Θ	O	▲	Θ	O	5	5	5	5
5	9	14.0	9.0	Efficiency	Θ	O	Θ	Θ	▲	Θ	Θ	Θ	▲	Θ	Θ	Θ	Θ	Θ	O	3	5	5	5
6	9	2.3	1.5	Portability	Θ	Θ	Θ	▲	▲	▲	O	O	Θ	Θ	▲	▲	▲	O	Θ	2	1	5	1
7	9	6.2	4.0	Manufacturability	Θ	Θ	Θ	Θ	O	▲	Θ	Θ	O	O	Θ	O	O	Θ	Θ	3	1	4	2
8	9	11.6	7.5	Power Consumption	Θ	Θ	Θ	Θ	▲	Θ	Θ	Θ	▲	Θ	Θ	O	Θ	Θ	O	5	5	5	3
9	9	13.2	8.5	Maintainance	Θ	Θ	Θ	Θ	O	Θ	O	Θ	O	Θ	Θ	O	Θ	Θ	Θ	3	2	2	4
10																							
				Target or Limit Value																			
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)																			
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9				
				Weight / Importance	800.8	714.0	900.0	881.4	355.8	517.1	602.3	571.3	377.5	727.9	881.4	427.1	608.5	707.8	465.9				
				Relative Weight	8.4	7.5	9.4	9.2	3.7	5.4	6.3	6.0	4.0	7.6	9.2	4.5	6.4	7.4	4.9				



Powered by QFD Online (http://www.QFDOnline.com)

Appendix J: Prioritizing Matrices

	1	2	3	4	5	6	7	8	9	10	11	12	13	Total	Factor
1. Cost		0.5	0	0	1	0	1	1	1	1	0	1	0	6.5	
2. Resistance to corrosion	0.5		0.5	1	0.5	0.5	1	1	1	1	0.5	1	0.5	9	
3. Water purification	1	0.5		1	0.5	0.5	1	1	1	1	0.5	1	0	9	
4. Power consumption	1	0	0		0.5	0.5	1	1	1	1	0.5	1	0	7.5	
5. Ease of use	0	0.5	0.5	0.5		0.5	1	1	1	1	1	1	0	8	
6. Low maintenance	1	0.5	0.5	0.5	0.5		1	1	1	1	0.5	1	0	8.5	
7. Manufacturability	0	0	0	0	0	0		1	1	1	0	1	0	4	
8. Portability	0	0	0	0	0	0	0		0.5	0	0	1	0	1.5	
9. Size	0	0	0	0	0	0	0	0.5		0	0	1	0	1.5	
10. Water capacity	0	0	0	0	0	0	0	1	1		0	1	0	3	
11. Life expectancy	1	0.5	0.5	0.5	0	0.5	1	1	1	1		1	0.5	8.5	
12. Aesthetics	0	0	0	0	0	0	0	0	0	0	0		0	0	
13. Safety	1	0.5	1	1	1	1	1	1	1	1	0.5	1		11	

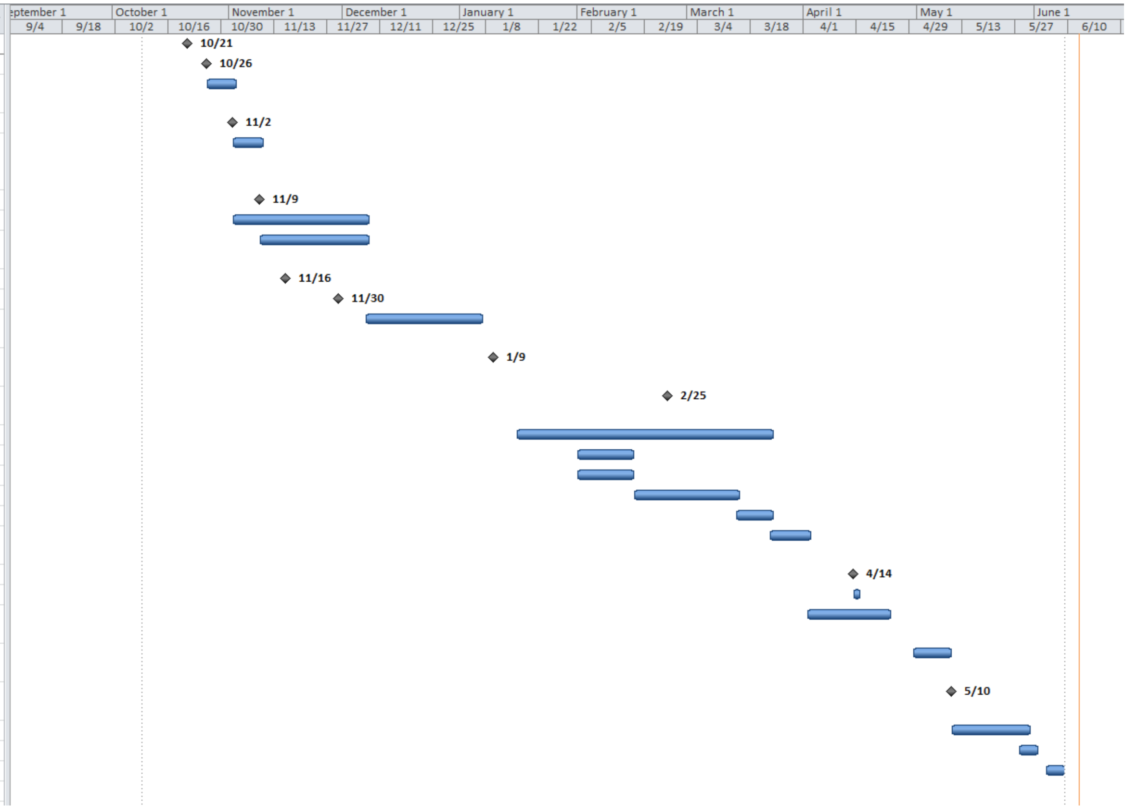
Appendix K: Project Design Specifications (PDS)

Project Design Specification		
Design Project: Solar Powered Water Purification System		
Team: Aqua Team	Date: April 15, 2012	Revision: 2
Datum Description: 2011 Team Clean Water System		

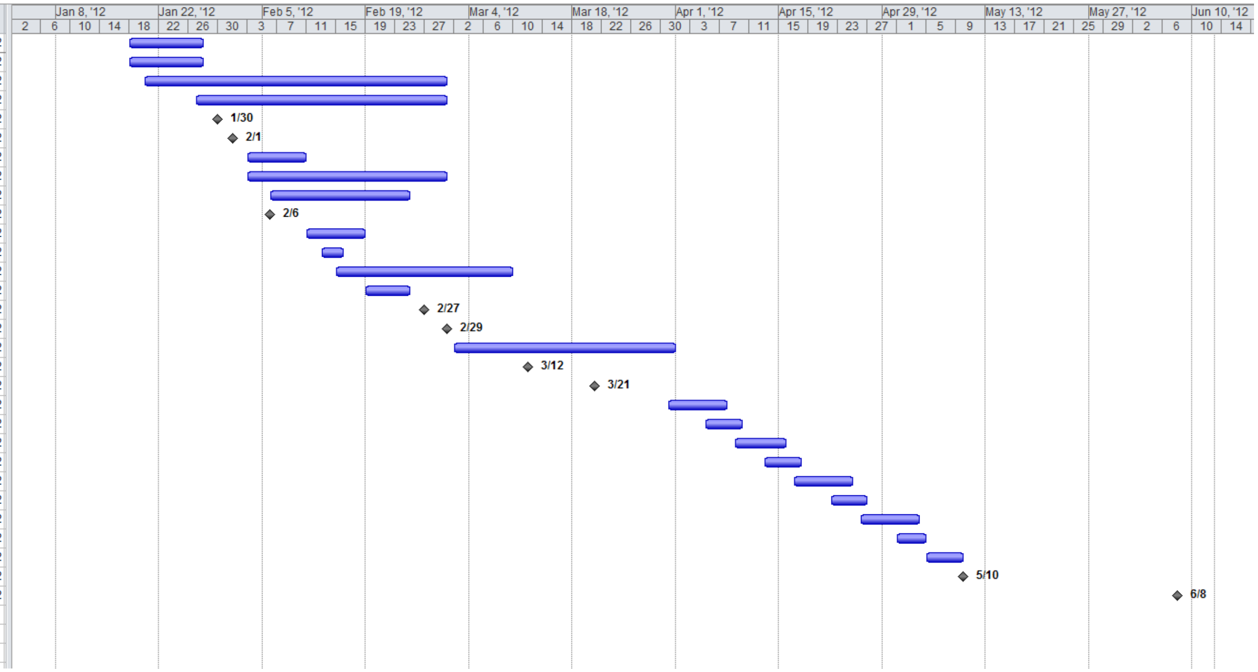
Elements/Requirements	Parameters		
	Units	Datum	Target-Range
Output Production	L/Day	11	38
Grid Power	Watts	500	0
Manufacturing Cost	Dollars	$6,500	$5,000
Retail Cost	Dollars	$10,900	$8,000
Temperature of Solar Collector	°C	70	115
Boiling Temperature	°C	38.7	100
Pressure of Water Vaporization	kPa	8	100
Weight	lbs.	500	400
Hours of Operation	hr.	8	8
Cleaning/Replacement	Months	6	1
Insolation	Yes/No	Yes	Yes
Target Market	Type	California Farmers	Developing Costal Communities
Input Water	Type	Salt/Brine/Brackish	Salt/Brine/Brackish
Output Water	Type	Distilled	Distilled
Control System	Type	Float Valve	Float Level Sensors, Solar Tracking, Solenoid Valve
Solar Collection	Type	Evacuated Tubes	Solar Troughs
Solar Collector Area	m^2	3	1.5
Collector Efficiency	%	70	70

Appendix L: Timeline

	Task Mode	Task Name	Duration	Start	Finish	Predecessors
10		Dean's Proposal Due	0 days	Fri 10/21/11	Fri 10/21/11	
11		Group Meeting	0 days	Wed 10/26/11	Wed 10/26/11	
12		Individual Concept Designs	6 days	Wed 10/26/11	Wed 11/2/11	
13		Group Meeting	0 days	Wed 11/2/11	Wed 11/2/11	
14		Review Concept Designs and Decide on Best Design	6 days	Wed 11/2/11	Wed 11/9/11	
15		Group Meeting	0 days	Wed 11/9/11	Wed 11/9/11	
16		Get System Operational	26 days	Wed 11/2/11	Wed 12/7/11	
17		Work on SolidWorks Model	21 days	Wed 11/9/11	Wed 12/7/11	
18		Group Meeting	0 days	Wed 11/16/11	Wed 11/16/11	
19		Group Meeting	0 days	Wed 11/30/11	Wed 11/30/11	
20		Research & Finalize Design/Parts	23 days?	Wed 12/7/11	Fri 1/6/12	
21		Parts List Due/Begin Ordering Parts	0 days	Mon 1/9/12	Mon 1/9/12	
22		Family Weekend Presentation	0 days	Sat 2/25/12	Sat 2/25/12	
23		Construct System	51 days	Mon 1/16/12	Fri 3/23/12	
24		Machine Boiler	11 days?	Wed 2/1/12	Wed 2/15/12	
25		Build Solar Trough	11 days?	Wed 2/1/12	Wed 2/15/12	
26		Configure Entire System	21 days?	Thu 2/16/12	Wed 3/14/12	
27		Primary Test of System	8 days	Wed 3/14/12	Fri 3/23/12	
28		Analyze Results and Decide on Adjustments	7 days	Fri 3/23/12	Mon 4/2/12	
29		Order Necessary Parts	0 days	Sat 4/14/12	Sat 4/14/12	
30		Preview Weekend	2 days?	Sat 4/14/12	Sun 4/15/12	
31		Make Necessary Adjustments to System	18 days	Mon 4/2/12	Mon 4/23/12	
32		Prepare for Design Conference	8 days	Mon 4/30/12	Wed 5/9/12	
33		Senior Design Conference	0 days	Thu 5/10/12	Thu 5/10/12	
34		Finish Senior Thesis	15 days	Thu 5/10/12	Wed 5/30/12	
35		Prepare for Open House	5 days	Mon 5/28/12	Fri 6/1/12	
36		Open House	5 days	Mon 6/4/12	Fri 6/8/12	



	Task Name	Duration	Start	Finish
1	Construct Ribs/Hangers	8 days?	Wed 1/18/12	Fri 1/27/12
2	Collect misc comp. for trough	8 days?	Wed 1/18/12	Fri 1/27/12
3	Aquire materials for foundation	34 days?	Fri 1/20/12	Wed 2/29/12
4	Buy clean water tank	29 days?	Fri 1/27/12	Wed 2/29/12
5	Budget update due	0 days	Mon 1/30/12	Mon 1/30/12
6	Have all trough components	0 days	Wed 2/1/12	Wed 2/1/12
7	Assemble trough #1	7 days?	Fri 2/3/12	Fri 2/10/12
8	Buy vapor pump	24 days?	Fri 2/3/12	Wed 2/29/12
9	Purchase main boiler components	18 days?	Mon 2/6/12	Fri 2/24/12
10	Drawings due	0 days	Mon 2/6/12	Mon 2/6/12
11	Trough testing	7 days?	Sat 2/11/12	Sat 2/18/12
12	Buy misc boiler components	3 days?	Mon 2/13/12	Wed 2/15/12
13	Purchase PV panel	21 days?	Wed 2/15/12	Fri 3/9/12
14	Assemble trough #2	6 days?	Sun 2/19/12	Fri 2/24/12
15	Analysis report due	0 days	Mon 2/27/12	Mon 2/27/12
16	Have all components for system	0 days	Wed 2/29/12	Wed 2/29/12
17	Assemble system	22 days?	Fri 3/2/12	Sat 3/31/12
18	Formal written and oral prog. report	0 days	Mon 3/12/12	Mon 3/12/12
19	Assembly drawings/hardware due	0 days	Wed 3/21/12	Wed 3/21/12
20	Troubleshoot/Test System #1	6 days?	Sat 3/31/12	Sat 4/7/12
21	Analyze data from Test #1	4 days?	Thu 4/5/12	Mon 4/9/12
22	Troubleshoot/Test System #2	6 days?	Mon 4/9/12	Sun 4/15/12
23	Analyze data from Test #2	4 days?	Fri 4/13/12	Tue 4/17/12
24	Troubleshoot/Test System #3	7 days?	Tue 4/17/12	Tue 4/24/12
25	Analyze data from Test #3	5 days?	Sun 4/22/12	Thu 4/26/12
26	Troubleshoot/Test System #4	6 days?	Thu 4/26/12	Thu 5/3/12
27	Analyze data from Test #4	4 days?	Tue 5/1/12	Fri 5/4/12
28	Prepare for Sr. Design Conference	4 days?	Sat 5/5/12	Wed 5/9/12
29	Sr. Design Conference	0 days	Thu 5/10/12	Thu 5/10/12
30	Sr. Thesis due	0 days	Fri 6/8/12	Fri 6/8/12



Appendix M: Budget Spreadsheets

Funding	Description	Amt. Received
	School of Engineering Grant	$3,000
	CSTS	$3,000
	TOTAL	$6,000

Subsystem	Component Description	Part #	# of Items	B/M/O	Cost/Part	Responsible Person	Total Cost
Controls	Arduino Mega	C027	1	O	55.09	Reece	55.09
	Thermocouple Shield	C028	1	O	72.16	Reece	72.16
	Solenoid Valve	C025	1	O	48.68	Reece	48.68
	20x4 LCD Module	C024	1	O	25.99	Reece	25.99
	Other Electrical Components						178
						SUBSYSTEM TOTAL	379.92

Solar	MC-4 Cable Adapter	S001	1	O	15.95	Reece	15.95
	Mercury Tilt Switch	S002	2	O	7.09	Reece	14.18
	MC-4 Extension Cable	S003	2	O	19.25	Reece	38.5
	Ball Bearing	S004	1	O	6.98	Erin	6.98
	Yoke End	S005	2	O	11.08	Erin	22.16
	Mounted Ball Bearing	S006	1	O	17.88	Erin	17.88
	Mounted Bronze Bearing	S007	1	O	13.1	Erin	13.1
	12 V Gear Motor	S008	1	O	64.15	Erin	64.15
	12 V, 50 AH Battery	S009	1	O	153	Reece	153
	120 W Solar Panel	S010	1	O	378.34	Reece	378.34
	Charge Controller	S011	1	O	39.91	Reece	39.91
	Solar Tracking Controller	S012	1	O	30	Reece	30
	Foam Strip	S013	2	B	4.84	Erin	9.68
	Arylic Mirror	S014	2	B	130.99	Erin	261.98
						SUBSYSTEM TOTAL	1065.81

Subsystem	Component Description	Part #	# of Items	B/M/O	Cost/Part	Responsible Person	Total Cost
Boiler/Condenser	RF-100 Vapor Pump	BC001	1	O	70.95	Andrew	70.95
	Duratherm 450 - 5 gal.	BC002	2	O	46.95	Alina	93.9
	Hot Loop Pump	BC003	1	O	579.99	Alina	579.99
	Copper HEX	BC004	1	B	39.99	Erin	39.99
						SUBSYSTEM TOTAL	784.83
Salt/Fresh Water	12 Gallon Tank	SF001	1	O	89.99	Alex	89.99
	Exapansion Tank	SF002	1	O	120	Alex	120
						SUBSYSTEM TOTAL	209.99
Foundation /Piping	Aluminum Tube, Square	FP001	3	B	14.81	Andrew	44.43
	HREW Tube, Round	FP002	1	B	13.87	Andrew	13.87
	Plywood	FP003	1	B	69.22	Reece	69.22
	Polyurethane Paint	FP004	1	B	18.27	Erin	18.27
	Trim Roller	FP005	3	B	5.73	Erin	17.19
	Edger Tray	FP006	2	B	1.94	Erin	3.88
	Valspar White Primer	FP007	1	B	20.98	Erin	20.98
	Copper Pipe 1"	FP008	2	B	42.64	Andrew	85.28
						SUBSYSTEM TOTAL	273.12

Total Cost	2713.67

Appendix N: Experimental Data

N.1 Preliminary Boiler Temperature Tests

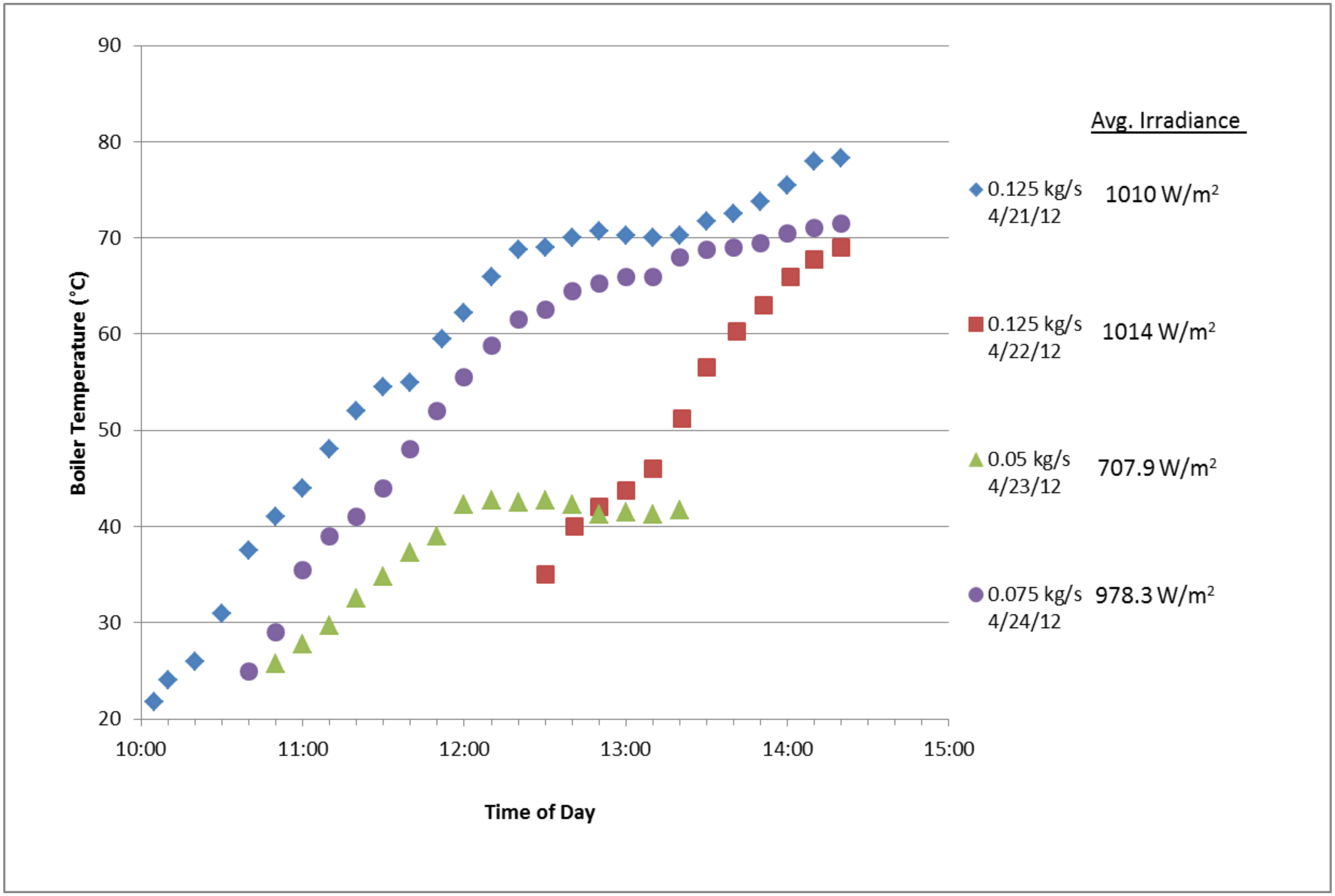
4/21/12	Initial Boiler Temp Test	
Mass Flow Rate = 0.125 kg/s		
Time	Boiler (°C)	Irradiance (W/m^2)
10:05	21.75	997
10:10	24	974
10:20	26	985
10:30	31	989
10:40	37.5	984
10:50	41	1009
11:00	44	1009
11:10	48	1015
11:20	52	1013
11:30	54.5	1014
11:40	55	1020
11:52	59.5	1023
12:00	62.25	1020
12:10	66	1024
12:20	68.75	1006
12:30	69	1008
12:40	70	1008
12:50	70.75	1006
13:00	70.25	1000
13:10	70	1019
13:20	70.25	1021
13:30	71.75	1013
13:40	72.5	1037
13:50	73.75	1027
14:00	75.5	1015
14:10	78	1018
14:20	78.25	1016

4/22/12	Initial Boiler Temp Test	
Mass Flow Rate = 0.125 kg/s		
Time	Boiler (°C)	Irradiance (W/m^2)
12:30	35	1004
12:41	40	977
12:50	42	1028
13:00	43.75	1019
13:10	46	1021
13:21	51.25	1017
13:30	56.5	1017
13:41	60.25	1021
13:51	63	1018
14:01	66	1022
14:10	67.75	1016
14:20	69	1009

4/23/12	Initial Boiler Temp Test	
Mass Flow Rate = 0.075 kg/s		
Time	Boiler (°C)	Irradiance (W/m^2)
10:50	25.75	992
11:00	27.75	1000
11:10	29.75	990
11:20	32.5	970
11:30	34.75	978
11:40	37.25	978
11:50	39	1039
12:00	42.25	409
12:10	42.75	520
12:20	42.5	479
12:30	42.75	416
12:40	42.25	419
12:50	41.25	501
13:00	41.5	409
13:10	41.25	481
13:20	41.75	746

4/24/12	Initial Boiler Temp Test	
Mass Flow Rate = 0.005 kg/s		
Time	B oiler (°C)	Irradiance (W/m^2)
10:40	25	1019
10:50	29	1138
11:00	35.5	1158
11:10	39	1100
11:20	41	1105
11:30	44	1020
11:40	48	1093
11:50	52	1050
12:00	55.5	1019
12:10	58.8	1053
12:20	61.5	1026
12:30	62.5	1016
12:40	64.5	992
12:50	65.25	1040
13:00	66	1070
13:10	66	1046
13:20	68	1000
13:30	68.75	1036
13:40	69	270
13:50	69.5	980
14:00	70.5	260
14:10	71	970
14:20	71.5	1040

N.2 Boiler Temperature Comparison of Preliminary Boiler Temperature Tests



N. 3 Adjusted Trough Temperature Tests

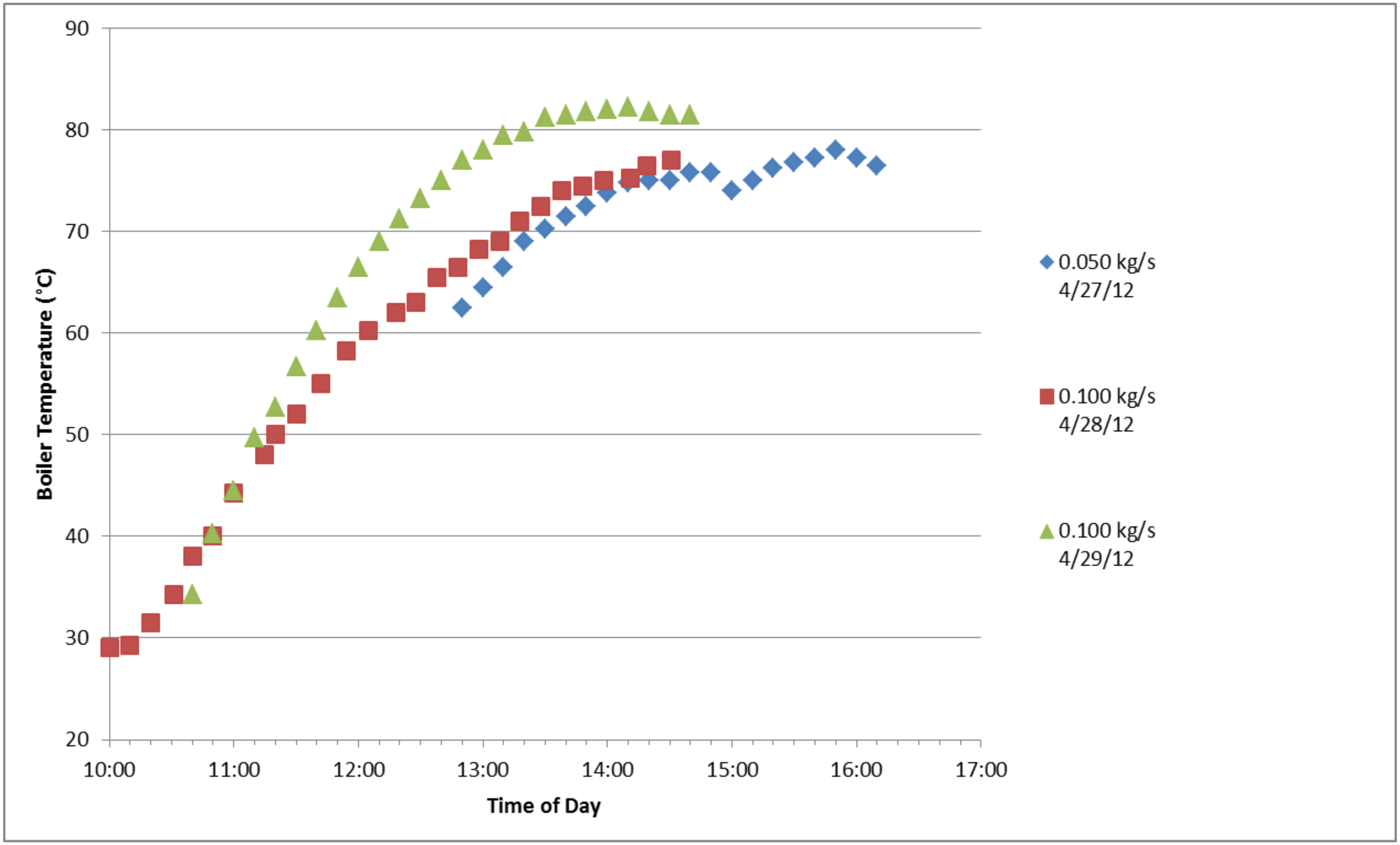
4/27/2012	Adjusted Trough Temp Test			
Mass Flow Rate = 0.050 kg/s				
Time	**Boiler Temp (°C)**	**Trough Inlet (°C)**	**Trough Outlet (°C)**	**Irradiance (W/m^2)**
12:50	62.5	57	66	998
13:00	64.5	59	68	995
13:10	66.5	60	69	1001
13:20	69	62	71	990
13:30	70.25	63	72	975
13:40	71.5	63	71	968
13:50	72.5	65	72	966
14:00	73.75	65	71	979
14:10	74.75	66	72	950
14:20	75	66	72	975
14:30	75	67	72	954
14:40	75.75	68	74	946
14:50	75.75	66	70	933
15:00	74	66	69	996
15:10	75	68	76	996
15:20	76.25	68	75	980
15:30	76.75	69	75	966
15:40	77.25	69	75	935
15:50	78	69	75	911
16:00	77.25	69	74	795
16:10	76.5	66	70	792
				974.5882

`

4/28/2012	Adjusted Trough Temp Test			
Mass Flow Rate = 0.100 kg/s				
Time	**Boiler Temp (°C)**	**Trough Inlet (°C)**	**Trough Outlet (°C)**	**Irradiance (W/m^2)**
10:00	29	19	19	920
10:10	29.25	25	26	945
10:20	31.5	30	32	961
10:31	34.25	34	36	968
10:40	38	36	38	950
10:50	40	37	4	983
11:00	44.25	42	45	986
11:15	48	45	49	980
11:20	50	46	49	982
11:30	52	48	52	970
11:42	55	52	56	960
11:54	58.25	54	59	980
12:05	60.25	54	59	988
12:18	62	56	60	980
12:28	63	57	62	997
12:38	65.5	58	62	970
12:48	66.5	59	63	981
12:58	68.25	61	65	975
13:08	69	63	67	990
13:18	71	65	70	992
13:28	72.5	65	70	981
13:38	74	67	71	981
13:48	74.5	67	71	990
13:58	75	68	72	1000
14:11	75.25	69	73	983
14:19	76.5	70	73	1000
14:31	77	71	75	998

4/29/2012	Adjusted Trough Temp Test			
Mass Flow Rate = 0.100 kg/s				
Time	**Boiler Temp (°C)**	**Trough Inlet (°C)**	**Trough Outlet (°C)**	**Irradiance (W/m^2)**
10:40	34.25	34	41	960
10:50	40.25	38	45	965
11:00	44.5	44	48	984
11:10	49.75	49	53	991
11:20	52.75	51	55	985
11:30	56.75	55	60	964
11:40	60.25	58	63	967
11:50	63.5	60	66	960
12:00	66.5	62	69	1090
12:10	69	64	70	981
12:20	71.25	67	73	984
12:30	73.25	68	75	989
12:40	75	69	75	990
12:50	77	72	78	998
13:00	78	72	77	1000
13:10	79.5	72	78	982
13:20	79.75	74	79	985
13:30	81.25	71	80	986
13:40	81.5	73	78	985
13:50	81.75	75	81	983
14:00	82	76	81	955
14:10	82.25	75	80	980
14:20	81.75	75	79	973
14:30	81.5	75	79	975
14:40	81.5	76	79	975

N.4 Boiler Temperature Comparison of Adjusted (Lowered) Troughs



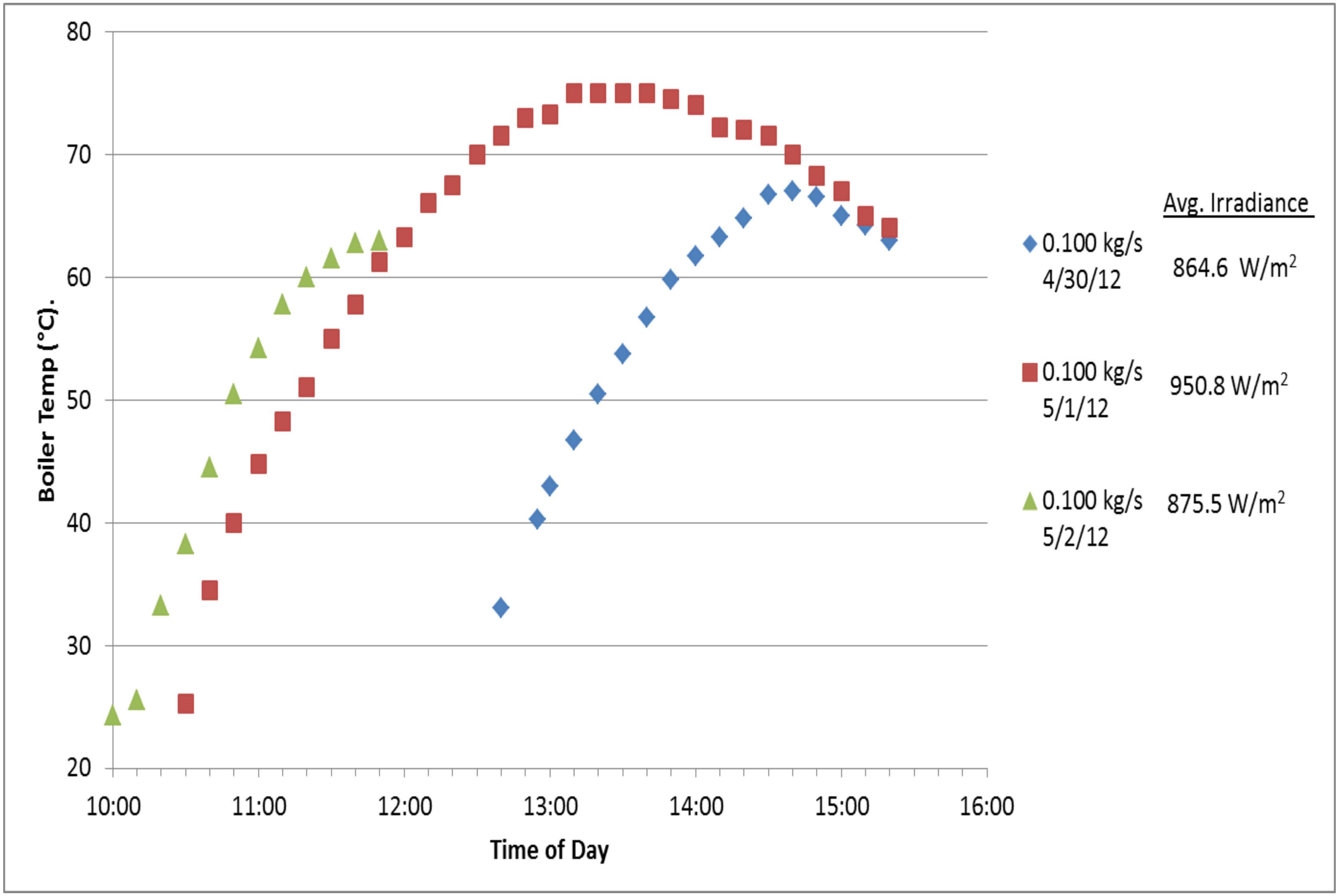
N.5 Temperature Tests with Convection/Radiation Envelope

4/30/2012	Temperature Test with Envelope			
Mass Flow Rate = 0.100 kg/s				
Time	Boiler Temp (°C)	Trough Inlet (°C)	Trough Outlet (°C)	Irradiance (W/m^2)
12:40	33	34	37	986
12:55	40.25	38	42	995
13:00	43	42	47	992
13:10	46.75	45	50	950
13:20	50.5	48	53	968
13:30	53.75	51	55	948
13:40	56.75	54	59	993
13:50	59.75	56	60	806
14:00	61.75	57	62	1014
14:10	63.25	59	63	638
14:20	64.75	60	65	930
14:30	66.75	62	66	743
14:40	67	61	64	780
14:50	66.5	58	60	670
15:00	65	56	58	870
15:10	64.25	57	59	353
15:20	63	55	56	1062

5/1/2012	Temperature Test with Envelope			
Mass Flow Rate = 0.100 kg/s				
Time	Boiler Temp (°C)	Trough Inlet (°C)	Trough Outlet (°C)	Irradiance (W/m^2)
10:30	25.25	26	44	965
10:40	34.5	35	39	982
10:50	40	38	41	964
11:00	44.75	43	48	980
11:10	48.25	47	51	1007
11:20	51	48	53	994
11:30	55	52	56	1003
11:40	57.75	54	59	999
11:50	61.25	57	62	1015
12:00	63.25	58	64	1008
12:10	66	59	64	993
12:20	67.5	60	66	997
12:30	70	63	68	977
12:40	71.5	63	68	1004
12:50	73	64	70	974
13:00	73.25	65	70	979
13:10	75	67	72	980
13:20	75	66	70	978
13:30	75	68	73	935
13:40	75	68	72	887
13:50	74.5	68	71	932
14:00	74	67	70	882
14:10	72.25	65	67	877
14:20	72	65	67	920
14:30	71.5	66	68	861
14:40	70	64	65	880
14:50	68.25	60	62	924
15:00	67	61	62	820
15:10	65	60	62	907
15:20	64	57	58	900

5/2/2012	Temperature Test with Envelope			
Mass Flow Rate = 0.100 kg/s				
Time	Boiler Temp (°C)	Trough Inlet (°C)	Trough Outlet	Irradiance
10:00	24.25	30	34	906
10:10	25.5	38	41	876
10:20	33.25	50	55	869
10:30	38.25	60	65	850
10:40	44.5	65	70	907
10:50	50.5	70	76	844
11:00	54.25	73	80	885
11:10	57.75	74	81	863
11:20	60	71	78	917
11:30	61.5	75	80	854
11:40	62.75	75	81	875
11:50	63	77	83	855
12:00	64	74	80	880

N.6 Boiler Temperature Comparison with Convection/Radiation Envelope



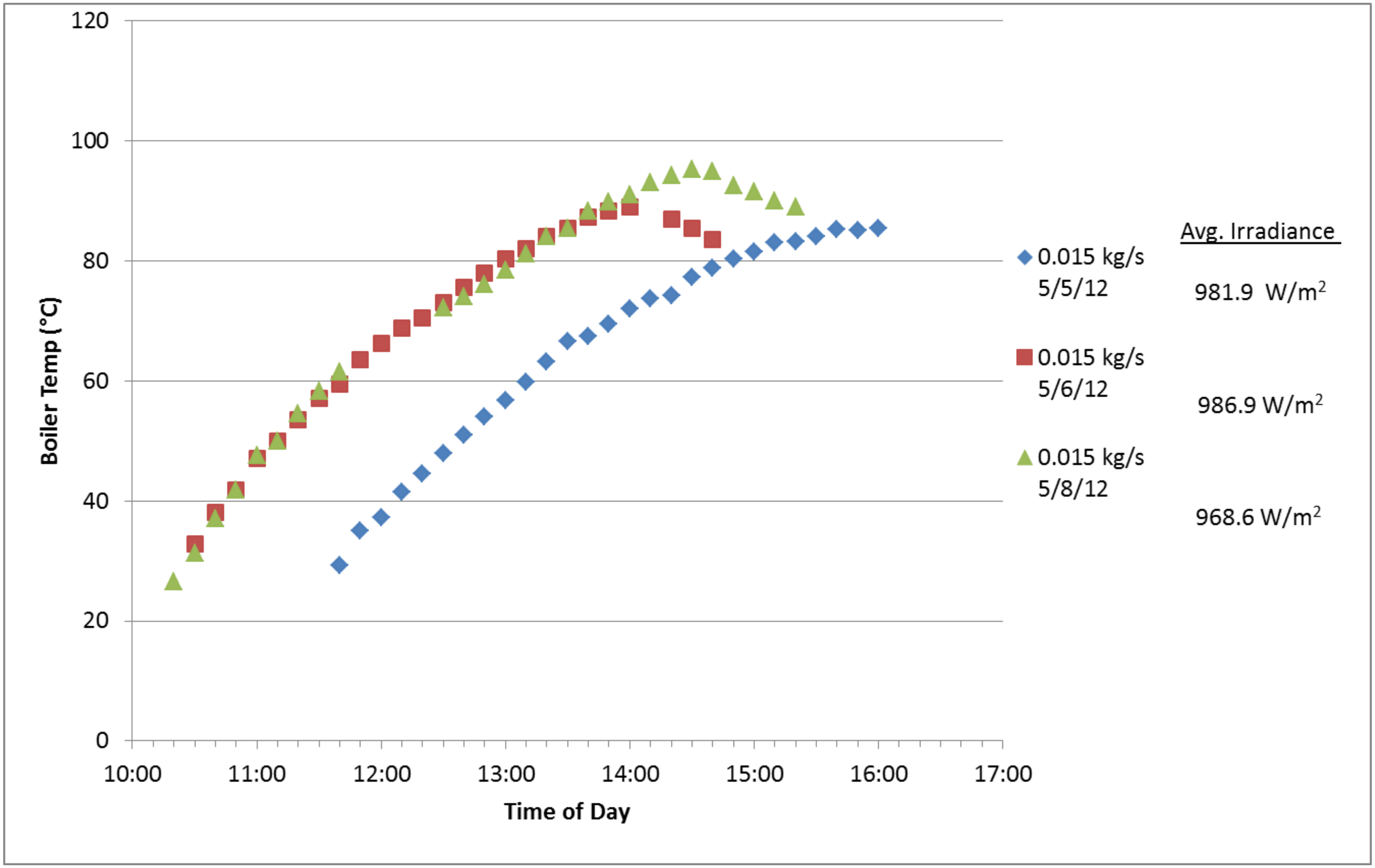
N. 7 Temperature Tests of Target EES Model Flow Rate

5/5/2012	Temp Test with EES Flow Rate			
Mass Flow Rate = 0.015 kg/s				
Time	Boiler Temp (°C)	Trough Inlet (°C)	Trough Outlet (°C)	Irradiance (W/m^2)
11:40	29.25	38	54	959
11:50	35	38	48	957
12:00	37.25	37	50	980
12:10	41.5	41	57	960
12:20	44.5	42	54	977
12:30	48	44	63	970
12:40	51	48	62	960
12:50	54	50	69	986
13:00	56.75	52	70	984
13:10	59.75	54	74	997
13:20	63.25	57	74	989
13:30	66.5	59	78	998
13:40	67.5	61	80	980
13:50	69.5	61	75	1002
14:00	72	65	83	1001
14:10	73.75	63	79	981
14:20	74.25	66	88	1003
14:30	77.25	68	84	991
14:40	78.75	70	90	991
14:50	80.25	70	86	982
15:00	81.5	72	94	999
15:10	83	73	87	980
15:20	83.25	73	91	982
15:30	84	74	93	980
15:40	85.25	74	90	970
15:50	85	74	91	973
16:00	85.5	74	84	956

5/6/2012	Temp Test with EES Flow Rate			
Mass Flow Rate = 0.015 kg/s				
Time	Boiler Temp (°C)	Trough Inlet (°C)	Trough Outlet (°C)	Irradiance (W/m^2)
10:30	32.75	29	46	964
10:40	38	37	56	968
10:50	41.75	39	61	972
11:00	47	44	67	977
11:10	50	45	67	980
11:20	53.5	47	78	968
11:30	57	50	73	988
11:40	59.5	53	85	970
11:50	63.5	56	82	967
12:00	66.25	58	86	995
12:10	68.75	58	91	966
12:20	70.5	60	88	998
12:30	73	61	98	975
12:40	75.5	63	92	990
12:50	78	66	103	981
13:00	80.25	68	92	994
13:10	82	68	105	986
13:20	84	69	98	997
13:30	85.5	72	108	1008
13:40	87.25	72	107	1015
13:50	88.25	72	106	994
14:00	89	72	107	1000
14:10	80	69	100	997
14:20	87	63	101	996
14:30	85.5	58	85	990
14:40	83.5	55	74	1000

5/8/2012	Temp Test with EES Flow Rate			
Mass Flow Rate = 0.015 kg/s				
Time	Boiler Temp (°C)	Trough In (°C)	Trough Out (°C)	Irradiance (W/m^2)
10:20	26.5	27	43	977
10:30	31.25	31	55	982
10:40	37	35	57	992
10:50	41.75	40	62	1002
11:00	47.5	46	71	985
11:10	50	46	80	995
11:20	54.54	50	82	980
11:30	58.25	54	83	964
11:40	61.5	56	79	975
12:30	72.25	66	81	997
12:40	74	67	80	963
12:50	76	71	87	951
13:00	78.5	73	86	1010
13:10	81.25	74	89	1002
13:20	84	78	94	984
13:30	85.5	80	94	1013
13:40	88.25	81	97	1000
13:50	89.75	82	94	990
14:00	91	84	99	990
14:10	93	84	94	985
14:20	94.25	84	97	999
14:30	95.25	85	95	953
14:40	95	83	86	612
14:50	92.5	80	84	990
15:00	91.5	78	81	997
15:10	90	80	84	1022
15:20	89	78	78	842

N.8 Boiler Temperature Comparison of Target EES Flow Rate



Appendix O: Arduino Code

```
// AQUA TEAM Control System 2012
// Solar Water Purification System
// Controls the system components through the use of sensors
// rev D -- updated 04/19/12

#include "max6675.h"
#include <LiquidCrystal.h>

// LCD Display
LiquidCrystal lcd(A0, A1, A2, A3, A4, A5);  // LCD pins

// Thermocouple
int thermoDO = 50;  // data out for MAX6675 thermocouple
int thermoCS = 48;  // CS for MAX6675
int thermoCLK = 52;  // clock for MAX6675 thermocouple
MAX6675 thermocouple(thermoCLK, thermoCS, thermoDO);
int vccPin = 46;  // vcc for MAX6675 thermocouple
int gndPin = 44;  // gnd for MAX6675 thermocouple

// Photocell
int photocellPin = A8;  // connected to cadmium sulfide photocell
int photocellReading;  // analog reading from the photocell

// Vapor Pump
int vaporpump = 10;  // connected to vapor pump transistor
int gndPin1 = 12;  // ground for vapor pump transistor

// HTF Pump
int htfpump = 11;  // connected to htf pump transistor for pwm
int gndPin2 = 15;  //ground for htf pump transistor
int LEDPin4 = 38;  //HTF LED
int LEDPin4gnd = 39; // gnd for HTF LED

// Float Switch
int vccPin3 = 9;  // vcc for top float switch
int gndPin3 = 8;  // gnd for top float switch
int top = 7;  // top float switch digital read
int topswitch;  // value for top float switch, 0 = open switch, 1 = closed switch
int vccPin4 = 6;  // vcc for bottom float switch
int gndPin4 = 5;  // gnd for bottom float switch
int bottom = 4;  // bottom float switch digital read
int bottomswitch;  // value for bottom float switch, 0 = open switch, 1 = closed switch
int val;  // sum of top and bottom

// Float Switch LEDs
int LEDPin1 =32;  // Float switch indicator LED 1
int LEDPin2 =34;  // Float switch indicator LED 2
int LEDPin3 =53;  // Float switch indicator LED 3
```

```
int LEDPin1gnd = 33;  // gnd for LED 1
int LEDPin2gnd = 35;  // gnd for LED 2
int LEDPin3gnd = 37;  // gnd for LED 3

// Solenoid Valve
int solenoidvalve = 30;  // connected to solenoid valve transistor
int gndPin5 = 2;  // gnd for solenoid valve transistor
int LEDPin5 = 42 ;  // LED for solenoid
int LEDPin5gnd = 41;  // gnd for solenoid LED

// Potentiometer
int potpin = A7;  // analog read for potentiometer
int vccPin6 = 26;  //vcc for potentiometer
int gndPin6 = 28;  //gnd for potentiometer
int potval;  // analog value for potentiometer

// Fan
int fan = A15;  // connected to fan transistor
int gndPin7 = 31;  // gnd for fan transistor

void setup() {
Serial.begin(9600);
// Set Arduino MEGA 2560 Pins
pinMode(vccPin, OUTPUT); digitalWrite(vccPin, HIGH);
pinMode(gndPin, OUTPUT); digitalWrite(gndPin, LOW);
pinMode(gndPin1, OUTPUT); digitalWrite(gndPin1, LOW);
pinMode(gndPin2, OUTPUT); digitalWrite(gndPin2, LOW);
pinMode(vccPin3, OUTPUT); digitalWrite(vccPin3, HIGH);
pinMode(gndPin3, OUTPUT); digitalWrite(gndPin3, LOW);
pinMode(vccPin4, OUTPUT); digitalWrite(vccPin4, HIGH);
pinMode(gndPin4, OUTPUT); digitalWrite(gndPin4, LOW);
pinMode(gndPin5, OUTPUT); digitalWrite(gndPin5, LOW);
pinMode(vccPin6, OUTPUT); digitalWrite(vccPin6, HIGH);
pinMode(gndPin6, OUTPUT); digitalWrite(gndPin6, LOW);
pinMode(gndPin7, OUTPUT); digitalWrite(gndPin7, LOW);
pinMode(fan, OUTPUT);
pinMode(top, INPUT);
pinMode(bottom, INPUT);
pinMode(LEDPin1, OUTPUT); digitalWrite(LEDPin1, LOW);
pinMode(LEDPin2, OUTPUT); digitalWrite(LEDPin2, LOW);
pinMode(LEDPin3, OUTPUT); digitalWrite(LEDPin3, LOW);
pinMode(LEDPin4, OUTPUT); digitalWrite(LEDPin4, LOW);
pinMode(LEDPin5, OUTPUT); digitalWrite(LEDPin5, LOW);
pinMode(LEDPin1gnd, OUTPUT); digitalWrite(LEDPin1, LOW);
pinMode(LEDPin2gnd, OUTPUT); digitalWrite(LEDPin2, LOW);
pinMode(LEDPin3gnd, OUTPUT); digitalWrite(LEDPin3, LOW);
pinMode(LEDPin4gnd, OUTPUT); digitalWrite(LEDPin4, LOW);
pinMode(LEDPin5gnd, OUTPUT); digitalWrite(LEDPin5, LOW);

lcd.begin(20,4);  // LCD size
```

```
// wait for MAX6675 chip to stabilize
delay(500);
}

void loop() {
// analog photocell reading
photocellReading = analogRead(photocellPin);  // get analog reading

// vapor pump control
if (thermocouple.readCelsius() >= 100 && photocellReading >= 500) {  // adjust strike
temperature and photocell reading
  digitalWrite(vaporpump, HIGH);  // turn on vapor pump
}

else  {
  digitalWrite(vaporpump, LOW);  // turn off vapor pump
}

// htf pump control
if(photocellReading > 500)  {  // adjust strike photocell reading      **** change to >600 ****
  potval = analogRead(potpin);  //  analog reading for potentiometer
  potval = map(potval, 0, 1023, 255, 0);  //  map analog reading to 8-bit
  digitalWrite(htfpump, HIGH);  //  turn on HTF pump
  analogWrite(fan, potval);  // output pwm for fan speed
  digitalWrite(LEDPin4, HIGH);  // turn HTF LED on

  delay(15);
}
else  {
  digitalWrite(htfpump, LOW);  // turn off htf pump
  digitalWrite(LEDPin4, LOW);  // turn HTF LED off
}

// Solenoid Valve Control
 topswitch = digitalRead(top);  // value for top float switch, 0 = open switch, 1 = closed switch
 bottomswitch = digitalRead(bottom);  // value for bottom float switch, 0 = open switch, 1 =
closed switch
 val = topswitch + bottomswitch;  // add top and bottom float switch values

if (val == 2) {  // if both switches are closed (Max Water Level)
  digitalWrite(solenoidvalve, LOW);  // close solenoid valve
  digitalWrite(LEDPin1, HIGH);  // All LEDs on, indicating boiler is full.
  digitalWrite(LEDPin2, HIGH);
  digitalWrite(LEDPin3, HIGH);
  digitalWrite(LEDPin5, LOW);  // solenoid LED off
}
if (val == 1) {  // if one switch is open (Moderate Water Level)
  digitalWrite(LEDPin1, LOW);  //LEDs 2 & 3 on, indicating boiler is draining.
  digitalWrite(LEDPin2, HIGH);
```

```
  digitalWrite(LEDPin3, HIGH);
}
if (val == 0) {  // if both switches are open (Low Water Level)
  digitalWrite(solenoidvalve, HIGH);  // open solenoid valve
  digitalWrite(LEDPin1, LOW);  //LED 3 on, indicating boiler is empty/filling
  digitalWrite(LEDPin2, LOW);
  digitalWrite(LEDPin3, HIGH);
  digitalWrite(LEDPin5, HIGH);  // solenoid LED on
}

// Print the current temp, analog photocell reading, switch values, sum, and valve setting
Serial.print("\n");
Serial.print("Boiler Temperature = ");
Serial.print(thermocouple.readCelsius());
Serial.print(" C");
Serial.print("\t");
Serial.print("Photocell Reading = ");
Serial.print(photocellReading);  // raw analog reading
Serial.print("\t");
Serial.print("   top switch: ");
Serial.print(topswitch);
Serial.print("   bottom switch: ");
Serial.print(bottomswitch);
Serial.print("   sum: ");
Serial.print(val);
Serial.print("   potval: ");
Serial.print(potval);

// LCD Formatting
lcd.setCursor(0,0);  // line 1, left margin (column, row)
lcd.print("***AQUA TEAM 2012***");
lcd.setCursor(0,1);  // line 2, left margin
lcd.print("Boiler Temperature");
lcd.setCursor(0,2);  // line 3, left margin
lcd.print(thermocouple.readCelsius());  // print thermocouple reading
lcd.setCursor(6,2);  // line 3, block 7
lcd.print("C");

 if (val == 2) {
  Serial.print("\t");
  Serial.print("--  Solenoid Valve Closed");
}
else if (val == 0) {
  Serial.print("\t");
  Serial.print("--  Solenoid Valve Open");
}

delay(1000);

}
```